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AUTOMOTIVE STIRLING ENGINE DEVELOPMENT PROGRAM

SEMIANNUAL TECHNICAL PROGRESS REPORT
FOR PERIOD: JANUARY 1 - JUNE 30, 1987

Mechanical Technology Incorporated

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Approved by: Roger A. Farrell
Roger A. Farrell
ASE Program Manager

Approved/Ratified by NASA: William A. Tomazic
William A. Tomazic

MECHANICAL TECHNOLOGY INCORPORATED
968 Albany-Shaker Road
Latham, New York 12110

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INTRODUCTION

In March 1978, a Stirling-engine development contract, sponsored by the Department of Energy (DOE) and administered by National Aeronautics and Space Administration (NASA)/Lewis Research Center, was awarded to Mechanical Technology Incorporated (MTI) for the purpose of developing an Automotive Stirling Engine (ASE) and transferring Stirling-engine technology to the United States. The program team consisted of MTI as prime contractor, contributing their program management, development, and technology-transfer expertise; United Stirling of Sweden (USAB) as major subcontractor for Stirling-engine development; and AM General (AMG) as major subcontractor for engine and vehicle integration.

Most Stirling-engine technology previously resided outside of the United States and was directed at stationary and marine applications. The ASE Development Program was directed at the establishment and demonstration of a base of Stirling-engine technology for the automotive application by September 1984. The high-efficiency, multifuel capability, low-emissions, and low-noise potential of the Stirling engine made it a prime candidate for an alternative automotive-propulsion system.

ASE program logic called for the design of a Reference Engine System Design (RESD) to serve as a focal point for all component, subsystem, and system development within the program. The RESD was defined as the best-engine design generated within the program at any given time. The RESD would incorporate all new technologies with reasonable expectations of development by the end of the program and which provide significant performance improvements relative to the risk and cost of their development. The RESD would also provide the highest fuel economy possible while still meeting other program objectives.

A schedule was defined within the ASE program to design two experimental engine versions of the RESD. The first-generation engine system, the Mod I, was designed early in the program and has been on test since January 1981. The second-generation engine, designated the Mod II, was originally scheduled to be designed in 1981 to demonstrate the final program objectives. However, it was postponed to 1984 due to Government funding cutbacks.

Through the course of the program, the Mod I has been modified and upgraded wherever possible, to develop and demonstrate technologies incorporated in the RESD. As a result, the program followed a "proof-of-concept" development path whereby an upgraded Mod I design emerged as an improved engine system, proving specific design concepts and technologies in the Mod II that were not included in the original Mod I design. This logic was recognized as having inherent limitations when it came to actual engine hardware, since Mod I hardware was larger and, in some cases, of a fundamentally different design than that of the Mod II.

Nevertheless, some of the new technology incorporated in the RESD has been successfully transferred to the upgraded Mod I engine. Iron-based materials were used in place of costly cobalt-based materials in the hot engine system (HES) that was designed to operate at 820°C heater head temperature (the Mod I was tested at 720°C). Smaller, lighter designs were incorporated into the upgraded engine to optimize for better fuel economy and to reduce weight (the upgraded Mod I engine was 100 lb lighter than the Mod I). The RESD has been revised periodically throughout the course of the program to incorporate new concepts and technologies aimed at improving engine efficiency or reducing manufacturing cost. The RESD was last revised in May 1983. Emphasis of this most recent update of the RESD was to reduce weight and manufacturing cost of the ASE to within a close margin of that for the spark-ignition engine, while exceeding the fuel mileage of the spark-ignition engine by at least 30%.

The 1983 RESD configuration was changed substantially from previous designs to achieve these goals. The new design used a single-shaft V-drive, rather than the two-shaft U-drive system of the Mod I; an annular heater head and regenerator rather than the previous cannister configuration; and a simplified control system and auxiliary components. By these measures, the projected manufacturing cost of the May 1983 RESD was reduced by more than 25% and total engine system weight was reduced by 47% in comparison to the upgraded Mod I engine, while engine efficiency and power remained approximately the same. This updated RESD has a predicted combined mileage of 41.1 mpg using unleaded gasoline, which is 50% above the projected spark-ignition engine mileage for a 1984 X-body vehicle with a curb weight of 2870 lb.

Since the RESD update in May 1983, the Mod II design effort has been focused on translating the RESD concepts into Mod II drawings. Casting drawings of the annular heater head and single-piece V-block were implemented and reviewed with vendors; the lower end drive system was designed for a durability rig to test the life and operational behavior of the bearings, seal systems, and gas passages. An analysis was performed on the Mod II engine/ vehicle system to select the vehicle and matching drive train components such as transmission, gear ratios, and axle ratio.

The preliminary design phase of the Mod II was concluded in September 1984 with a Technology Assessment which selected specific technologies and configurations from competing contenders for each component of the Mod II engine. These component configurations were then moved into the initial detail design phase where the design was completed in preparation for manufacturing. Component development was intensified for certain components that needed further improvements; combustion gas recirculation (CGR) combustor, as well as controls and auxiliaries. The Spirit vehicle with upgraded Mod I engine No. 8, after the successful completion of its testing during the General Motors (GM) portion of the Industry Test and Evaluation Program (ITEP), was utilized to evaluate new controls and auxiliaries concepts to be incorporated in the Mod II. Analysis efforts were concentrated on finalizing loss models and algorithms for all aspects of the Mod II engine, which were then integrated into computer codes to be used in optimizing the engine.

In January 1985, the CGR combustor external heat system (EHS) was selected as the prime design, and the first optimization of the Mod II was completed. This optimization identified key engine parameters such as power and efficiency levels, bore and stroke, as well as key component design specifications, such as preheater plate aspect ratios, regenerator and cooler dimensions, etc. This initial optimization was then honed and refined through many successively smaller iterations, including a preliminary final version presented at the basic Stirling engine (BSE) Design Review, until the design was finalized at the Stirling engine system (SES) Design Review in August 1985. Improvements in the projected Mod II engine design and performance resulted from vendor feedback on the prototype Mod II V-block and heater heads, from component development tests of low idle fuel consumption and from extended Mod I engine testing of seals, piston rings and appendix gap geometry. During this period as well, a 1985 Celebrity with a 68.9 kW (92 hp) I4 engine was selected for the Mod II vehicle installation. This vehicle is representative of the vehicle class (3000-

3500-lb front-wheel drive) that is extremely popular in the U.S. automotive market. It also has the best fuel economy in its class, thereby establishing a high-level internal combustion (IC) reference mileage for the Mod II evaluation.

The BSE and SES Mod II designs were both completed on schedule, and the design was approved by NASA for manufacture. The final performance predictions indicate the Mod II engine design will meet or exceed the original program goals of 30% improvement in fuel economy over a conventional IC powered vehicle, while providing acceptable acceleration and emissions. This was accomplished while simultaneously reducing Mod II engine weight to a level comparable with IC engine power density, and packaging the Mod II in a 1985 Celebrity with no external sheet metal changes. The projected mileage improvement of the Mod II Celebrity for the combined urban and highway CVS cycles is close to 30% relative to the IC Celebrity. If additional potential improvements are verified and incorporated in the Mod II, the mileage improvement could increase to more than 30%.

The Mod II engine start date of 31 January 1986 was met, using a machined analog V-block and manifold-type (configuration 1) heater heads in place of the cast block and no-manifold (configuration 4) heater heads, which were not complete.

During this semiannual report period, an additional 316 hours were accumulated on the Mod II analog block engine bringing the total to 538 hours. Earlier problems with various parts of the cold engine and drive system (CEDS) were overcome. This statement can be made with confidence as 316 hours were achieved on the ion-nitrided coolers, main seals, and piston rings; 525 hours on the drive system; and 353 hours on the crosshead liners. As a result, substantial development testing was completed. This included BSE performance, emissions, and noise characterization as well as the demonstration of the impact of regenerator porosity, working gas, and no-manifold heater heads on performance. Based on the test results of the first set of no-manifold heater heads, designated configuration 4L, an improved version (configuration 4S) was designed featuring shorter tubes, fewer bends, and enhanced rear-row heat transfer that will enable the program fuel economy goal (30% relative to an IC-powered vehicle) to be demonstrated. Deere and Company performed a value analysis/value engineering study, which revealed that substantial savings are possible for a mass-produced Mod II engine.

Fatigue testing of the Mod II piston rod assembly, used with single-solid piston rings, revealed an inadequacy in the fabrication process resulting in unacceptable life. This led to a design modification to the existing split-solid type rod, which has acceptable fatigue life, so that they can be used with single solid piston rings. Motoring rig testing of the Mod II cast V-block with Koyo rolling-element bearings successfully demonstrated 10 hours of life at maximum speed and pressure. In support of Mod II development, existing upgraded Mod I engines and bench rigs were used to develop Mod II SES hardware. Improvements were identified for the DAFC, blower drive system, battery charge circuit, and atomizing air compressor. The mean pressure control (MPC) and combustion air blower were proven adequate for use on the Mod II.

The Mod I and upgraded Mod I engines reached 17,835 hours in support of Mod II development and the NASA Technology Utilization (TU) vehicles. The Phase I TU van completed its evaluation by the U.S. Air Force at Langley Air Force Base burning gasoline, JP-4, and diesel fuel. A second Phase II TU vehicle was selected to be a Dodge D-150 pickup truck and conversion to Stirling power begun.

During the next semiannual report period, a Mod II cast block engine will become operational. It will be installed in the test cell to demonstrate the feasibility of single solid piston rings and complete SES characterization and then, at the beginning of the next report period, be installed into a vehicle. A second cast block Mod II engine will also be built. It will be installed in the test cell after the first engine is removed and used to test the configuration 4S heater heads.

I. SUMMARY

Substantial progress was made during this report period, demonstrating that previous mechanical problems have been solved and in completing most of the basic Stirling engine (BSE) development testing. In the former case, 316 to 525 hours were achieved without wear or failure of components that had previously been unreliable or lacked durability; that is, coolers, crossheads, crosshead liners, and piston rings. During testing, predicted levels of power and efficiency at maximum power were demonstrated, low emissions and optimal regenerator porosity confirmed, the validity of Stirling analytical codes with various working gases demonstrated, performance of the external heat system (EHS) optimized, noise levels determined, and the feasibility of fabricating no-manifold configuration 4 heater heads proven. At the end of this semiannual report period, Mod II analog block engine No. 1 had achieved 538 hours of operation, 316 hours in this report period. A second engine with a cast block successfully completed its initial evaluation as a motoring unit, achieving 53 hours, 10 of them at maximum speed and pressure.

Hardware development included no-manifold configuration 4 heater heads, single solid piston rings, and coolers. Testing of the configuration 4 heater heads revealed no performance improvement compared to the two-manifold configuration 1. This was due to modifications made to the design to enable fabrication. The longer-than-intended tubes of configuration 4L with many sharp bends resulted in increased dead volume and pumping losses that adversely impacted performance. The revised configuration 4S design incorporates corrections for the fabrication problems encountered with 4L, shorter tubes, reduced bend losses, and enhanced rear row fin area.

Procurement of configuration 4S was initiated with completion expected during the next semiannual period. Fatigue testing of the hollow piston rod used with single solid piston rings indicated improper material preparation (i.e., inadequate hardness, oxidation during heat treatment, and improper heat treatment). Rather than fabricate new rods, a long and expensive process, it was decided to modify existing rods used with split-solid piston rings. Previously unacceptable cooler/piston ring wear was overcome by using ion-nitrided or aluminum-oxide-coated coolers.

A value analysis/value engineering cost study of the Mod II engine was initiated by Deere and Company. As of the end of this report period, 76% of the manufactured parts of the engine have been evaluated and savings of 32% (CEDS) and 49% (EHS, HES, controls, and auxiliaries) identified if manufactured in quantities of 15,000/yr.

Mod II Engine Development

Emphasis of the program is now on the Mod II engine to be used to demonstrate the program goals. Hence, upgraded Mod I engines were used as component development test beds for the Mod II or for technology utilization (TU) until Mod II engines are available for that purpose. Two upgraded Mod I engines were used for Mod II component development; the first (engine No. 10) demonstrating the feasibility of single solid piston rings and the second installed in the Spirit vehicle (engine No. 8) for controls and auxiliaries development, for a combined total of 258 hours.

Upgraded Mod I engine No. 5 accumulated 853 hours installed in a U.S. Air Force multistop van during the report period, completing its test evaluation at Langley

Air Force Base. A total of 1216 hours have been achieved burning gasoline (527), JP-4 (536), and diesel (153). The success of this demonstration led to a second vehicle test program being initiated. The Dodge D-150 pickup truck will finish conversion to Stirling power in the next report period and be evaluated at different U.S. Air Force bases to ascertain over-the-road capabilities under a variety of environmental conditions.

Total Mod I hours are 17,835, 1247 in this report period.

Component and Technology Development

Activities in this area concentrated on the final development of Mod II components, specifically the conical fuel nozzle, controls, and auxiliaries. A total of 2184 hours of plug-free operation has been demonstrated by the conical fuel nozzle in various Mod I and Mod II installations. The Spirit vehicle was utilized to finalize the development of the Mod II Stirling engine system (SES). Specifically, digital air/fuel control (DAFC) calibration and temperature sensitivities inadequate atomizing airflow, poor blower drive system reliability, and battery charge circuit interference with the digital engine control (DEC) were identified. This resulted in the design of an improved DAFC utilizing standard automotive components, reconfigured atomizing air compressor plumbing, and redesigned blower drive and battery charge electronics.

The mean pressure control (MPC) has proved to be reliable and functions as designed. This system, including the two-tank system and three-volume hydrogen compressor, demonstrated improved transient performance compared to its Mod I counterpart. The H_2 compressor passed a 500-hr durability test. Similarly, the combustion air blower has demonstrated performance close to original design predictions.

II. COMPONENT AND TECHNOLOGY DEVELOPMENT

External Heat System Development

The primary goal of the EHS is low emissions while maintaining high efficiency for a 30:1 fuel turndown ratio in a minimum volume.

The design must consider durability, heater head temperature profile, and use of alternative fuels while recognizing the significant cost impact of system size and design.

Emphasis during the first half of 1987 was directed toward completing development of the 3-hole conical nozzle and supporting Mod II engine and vehicle testing. Major activities during this period included the selection of an integral igniter conical nozzle for the Mod II, improving the durability of the Mod II CGR combustor, defining Mod II combustor operating parameters, and support for the alternative fuel operation of the NASA TU Stirling-powered van.

During the next semiannual report period, development of an improved durability combustor will be completed; support will be provided to the Mod II engine, Celebrity vehicle, and NASA TU vehicles; and fabrication of two ceramic preheater test blocks will be completed.

Conical Nozzle Development

The objective of conical nozzle development is to eliminate fuel nozzle plugging; minimize heater head temperature variations, soot, and gaseous emissions; and reduce atomizing airflow to 0.4 g/sec at idle.

The objective of plug-free operation has been obtained with the 3-hole conical nozzle. As of the end of June, a total of 2184 hours of plug-free operation had been obtained with six nozzles:

Installation	Nozzle No.	Hours
NASA TU Van	1	981.8
	2	167.4
NASA TU Van (Spare)	3	350.1
Mod II Engine No. 1	4	383.2
Spirit Vehicle	5	230.8
	6	70.6
		2183.9

Efforts to incorporate an igniter into the 3-hole conical nozzle design (simplified combustor and EHS cover design) considered both center (Figure 2-1)* and integral (Figure 2-2) locations. In the former case, 15 center igniter versions were rig tested before concluding that the changes introduced to the fuel and atomizing air passages, necessitated by the igniter location, adversely affected combustor performance. These adverse affects were manifested by unacceptably high soot and heater head temperature variation levels.

Use of an integral (to the nozzle body) igniter allows the internal aerodynamics to be retained. In this case, however, the concern is ignition capability, igniter life, and possible disruption to combustor flow patterns. In order to address the question of ignition capability, a test was conducted with the Spirit vehicle. Two integral approaches were evaluated: through the nozzle retaining bolt (i.e., parallel to the nozzle body as currently used for the Mod II engine and upgraded Mod I vehicles, Figure 2-3)

*Figures are at end of this section, beginning on page 2-15.

and angled.* In either case, ignition delay and tube temperature rise times were acceptable and comparable. Typical data are illustrated in Figures 2-4 and 2-5. Experience with the through-the-bolt approach has indicated no affect on combustor aerodynamics but poor reliability. The reliability is addressed by the nozzle body, incorporating an angled igniter of a more substantial design, as shown in Figure 2-2. This integral igniter design has been procured and will be tested in Mod II engine No. 1.

Except for demonstrating igniter durability, nozzle development is considered complete.

Mod II CGR Combustor Durability

The objective of combustor durability is to obtain a combustor life of 3500 hours and 10,000 starts. The Mod II combustor with its thin-shelled (0.5 mm versus 1.25 mm for Mod I) and corrugated material has proven to be unsatisfactory with a life under 200 hours. The thin shell, used to reduce cold start penalty, is subject to both cracking and sagging, leading to disruption of combustion flow patterns and nozzle misalignment, respectively.

Efforts to improve durability have included reinforcing the center section with extra high-strength material (Inconel), eliminating the bellows seal (Figure 2-2), sealing the top of the combustor from high-pressure air (Figure 2-6), and using a brazed assembly. The reinforcing approach was an interim measure until hardware for the other concepts could be procured.

Elimination of the bellows seal was done to remove a failure-prone item and provide a more positive means of aligning the fuel nozzle to the combustor and heater head. At the same time, the cover was also modified to accept the integral igniter conical nozzle. The purpose of the sealed combustor is to remove the pressure gradient from the combustor shell. This piece is subjected to high temperatures and, hence, loses most of its strength. After time, the shell would sag and eventually form cracks under the pressure gradient.

Experience to date has demonstrated an improvement in combustor life of at least 100 hours with the reinforced center section. Hardware for the nonbellows seal and sealed combustors was ordered and will be evaluated in the Mod II engine during the next reporting period.

Engine/Vehicle Support

The objectives of engine/vehicle support are twofold. First, it is to ensure that the Mod II engine meets the program emissions goals (g/mi):

NO_x:	0.40
CO:	3.40
HC:	0.41
Particulates:	0.20

with soot-free combustion (Bacharach ≤ 2) and low heater head temperature variation ($\Delta T \leq 100°C$) over a 30:1 fuel turndown ratio.

The second objective is multifuel capability** of the upgraded Mod I engine used in the NASA TU program. The requirements here are soot-free operation with a heater head variation $\leq 100°C$ over a 9:1 fuel turndown ratio.

The Mod II emissions were evaluated in two phases using engine No. 1. Initial mapping was conducted at lambda (λ) = 1.25 and atomizing airflow = 1.0 g/sec. The engine was equipped with a CGR combustor and 3-hole conical nozzle and operated at an 820°C set temperature.*** Results indicated heater head ΔT and

*Aerodynamically the same as Figure 2-2.
**Unleaded gasoline, JP-4, and diesel.
***Except at low fuel flows where a lower temperature is used.

smoke number (soot) within design limits, except over a narrow range of fuel flows (Figures 2-7 and 2-8). NO_x and CO emissions were projected to be slightly in excess and within CVS cycle requirements, respectively (Figures 2-9 and 2-10). HC emissions were so low that they were virtually unmeasurable and are not shown.

During the second test series, atomizing airflow and lambda were varied to determine optimum conditions. From an efficiency standpoint, it is desirable to minimize both parameters with the goal being 0.36 g/sec and 1.25, respectively. The limitations are that soot, heater head ΔT, and NO_x may be affected. The testing indicated that soot and NO_x emissions are sensitive to atomizing airflow (Figures 2-11 and 2-12) with the main limitation being soot. Based on this, the minimum acceptable atomizing airflow is defined in Figure 2-13 indicating the goal is achieved only at idle. Heater head temperature variation was virtually unaffected by atomizing airflow (Figure 2-14). Varying lambda was found to have much less of an impact than varying atomizing airflow. The schedule selected for the Mod II, based on these tests, is illustrated in Figure 2-15. An on/off atomizing airflow schedule was selected for control simplicity. The variation in lambda at high fuel flows is based on blower capacity limitations.

The support for the NASA TU program included establishing lambdas for operation on JP-4 and diesel and assisting in the development of the gasoline start-up system used with diesel operation. Details of this work are described in "Phase I Air Force Van," Section IV.

Ceramic Preheater Development

The objective of ceramic preheater development is to demonstrate the feasibility of fabricating low-cost ceramic matrices by producing several mixed-oxide preheater blocks that will have less than 5% leakage after 300 thermal cycles.

Following the successful fabrication of a mixed-oxide block using new binders (reported in MTI Report 87ASE555SA11), an additional two blocks have been procured from Coors Porcelain Company. Fabrication has begun with completion expected during August 1987. At that time, the blocks will be evaluated for integrity (internal leaks).

Materials and Process Development

The goal of materials and process development is the utilization of low-cost, low-strategic element content materials in the ASE, capable of surviving 3500 hours of automotive duty cycle exposure. Additionally, this task provides materials support to the Mod II design and component development activities.

Accomplishments during the first half of 1987 included continued proof/fatigue testing of the Mod II piston rod/base/crosshead for single solid piston rings and configuration No. 4 heater head, as well as the completion of heater tube material creep tests.

Activities planned for the next report period include continued proof/fatigue testing of the Mod II configuration No. 4 heater head and general materials support.

Mod II Piston Rod/Base/Crosshead Fatigue Test

The objective of this task is to develop a fatigue-resistant piston rod/base/crosshead assembly for use with Mod II single solid piston rings. The design change to unvented piston rods, used with these rings, necessitated the proof-fatigue testing of the new configuration. The piston rods are the same as those used with Mod I type split-solid piston rings, except that the minimum pressure (P_{min}) hole is removed and a 1.5-mm hole is put along the centerline of the piston rod through the center drill hole in the shank end to the countersink, as shown in Figure 2-16.

During this report period, six piston rods were subjected to proof/fatigue testing. Samples No. 9 and 10 were manufactured from previously manufactured Mod II P_{min} vented design piston rods. The last three were actual Mod II, completely finished piston assemblies. The test cycle is shown in Table 2-1.

TABLE 2-1
FATIGUE TEST CYCLE

Step	No. of Cycles	% of Full Load
1	10^7	100
2	10^6	120
3	10^6	140
4	10^6	150
5	10^6	160

Only partial success was achieved with these tests, as shown in Table 2-2.* While none of the samples survived the complete test cycle, the third test demonstrated the feasibility of the design if material and process are done correctly.

The tests also showed how sensitive the piston rods are to manufacturing process variables. It was found that it is necessary to ensure that rough-machined surfaces be protected from oxidizing environments during all heat-treating processes and that surfaces be protected from rusting during storage. It was also noted that strict quality control measures must be used to ensure adherence to drawing heat-treat requirements.

The optimum process demonstrated during the third test in this report period consisted of a piston rod that had been shot peened over its entire crosshead end. The shot peening imparts a compressive stress on the surface of the piston rod to a depth of about 0.004 in. The compressive stress raises the amount of applied tensile stress required to initiate fatigue cracking. Based on these results, the hardware was considered unacceptable for engine use because of material and/or processing defects.

Configuration No. 4 Heater Head Casting Fatigue Test

A Mod II configuration No. 4 heater head was subjected to proof/fatigue testing to verify that the design, material, and processing of the assembly meets the intended requirements and is acceptable for engine hardware. The test assembly consisted of a cast and machined HS-31 heater head casting and Inconel 625 stub heater tubes brazed with Nicrobraze LM. The assembly was clamped to a test plate with a stuffer to take up hydraulic oil volume.

The test cycle sequence consists of the following steps.

1. 10^7 cycles at 15.0 ±5 MPa (100% load)
2. 10^6 cycles at 16.87 ±5.625 MPa (112.5% load)
3. 10^6 cycles at 18.75 ±6.25 MPa (125% load)
4. 10^6 cycles at 20.625 ±6.875 MPa (137.5% load)
5. 10^6 cycles at 22.5 ±7.5 MPa (150% load)

Steps 1, 2, and 3 have been completed. However, the testing has been interrupted because the heater head clamping bolts have failed twice by fatigue. The first bolt failure occurred after 774,000 cycles at the 125% level. New bolts were installed, and the second failure occurred after 349,100 cycles at the 137.5% load level. The bolts are ISO Grade 12.9 and were found to be of acceptable quality. The design of the clamps is being reviewed. Testing will resume as soon as design changes are implemented.

*Table 2-2 is on the following page.

TABLE 2-2
TEST RESULTS SUMMARY
MOD II SINGLE SOLID TYPE PISTON
BASE/ROD/CROSSHEAD PROOF/FATIGUE TEST

Fatigue Sample No.	Configuration	No. of Cycles at Failure	% of Full Load Level at Failure	Comments
8	Mod II piston rod test section	1.2×10^6	100	Not shot peened. Fatigue failure at thread root.
9	Remanufactured from P_{min} vented design	3.3×10^6	100	Partially shot peened. Fatigue failure at at corrosion pit.
10	Remanufactured from P_{min} vented design	0.185×10^6	140	Fully shot peened. Fatigue failure at heat treat defect.
11	Mod II piston assembly	4.7×10^6	100	Partially shot peened. Fretting fatigue at local contact with crosshead.
12	Mod II piston assembly	0.644×10^6	100	Fully shot peened. Tensile overload. Inadequate heat treatment.
13	Mod II piston assembly	0.375×10^6	100	Fully shot peened. Fatigue failure at oxidized internal surface. Inadequate heat treatment.

Heater Tube Material Creep Rupture Test

Testing of candidate heater tube materials was conducted at representative design and elevated temperatures. The reference alloy, N-155, and the following five candidate alloys were selected for creep rupture evaluation.

- 12RN72. An austenitic, iron-base, stainless steel with enhanced corrosion resistance, and titanium and boron for elevated temperature creep strength.

- Sanicro 31H. An iron/nickel base, nitrogen-strengthened alloy similar to Inconel 800H.

- Sanicro 32. An iron/nickel base, tungsten version of Sanicro 31H.

- CG-27. An iron/nickel base, precipitation hardened alloy strengthened with columbium, titanium, and aluminum.

- Inconel 625. A nickel-base, solid-solution-strengthened alloy.

The candidate alloys were selected for low cost, availability, low strategic material content, brazeability, formability, and creep strength at heater tube temperatures. The nominal composition of each alloy is shown in Table 2-3.* Representative design temperatures were 750 and 850°C corresponding to set temperatures of 720 (P-40, Mod I) and 820°C (upgraded Mod I, Mod II), respectively. Test results at 850°C are illustrated in Figure 2-17 and Table 2-4.* The conclusion was that CG-27 was superior to the others.

The elevated temperature tests were conducted using CG-27 and Inconel 625 at temperatures of 900 and 950°C. CG-27 was also used to test a new heat treatment, which shortens the cycle and reduces production costs. The Inconel 625 results, Figure 2-18, indicate that it is not strong enough at 900°C to meet the design goals (28 MPa at 3500 hr). The design goal does include a safety factor of 1.5. The CG-27 material, however, is capable of operation at 900°C, Figure 2-19.

The shortened heat-treat cycle for GC-27 is a single step of heating to 1450°C for 4 hours, followed by cooling to room temperature. The regular recommended process (Crucible Steel) is two steps: 1) heat to and hold at 1450°F for 16 hours, then air cool, and 2) heat to and hold at 1200°F for 16 hours, then air cool. Comparing the results indicated the shortened process led to enhanced creep rupture at 850°C and similar performance at 900°C, Figure 2-20.

Cold Engine System (CES) Development

The primary objective of CES activity is to develop reliable, effective, long-life rod seals, piston rings, and static seals. Activity during the reporting period has been primarily concerned with evaluating piston ring performance in engines and determining Mod II engine H_2 leakage rates.

Piston Rings

The Mod I engine design has two piston ring grooves on each piston and each groove houses two piston rings, one solid and the other jointed. The space between the two grooves is maintained at the minimum cycle pressure, which ensures that the pressure difference across each groove is always in the same direction.

Alternative designs have been developed for the Mod II in which there is only one piston ring per piston, a much simpler arrangement. Engine tests have shown that the single rings perform as well as the double rings, if not better. With the single rings, leakage across the rings passes from cycle to cycle and

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Tables 2-3 and 2-4 are on the following page.

TABLE 2-3
CANDIDATE HEATER TUBE ALLOYS
NOMINAL COMPOSITIONS

Alloy	Composition (%)													
	Co	Cr	Ni	Mo	W	C	Al	Ti	B	Cb	Nm	Fe	Si	N
Multimet (Ref.)	19.75	21.25	20.0	3.0	2.5	0.12	-	-	-	1.0	1.5	29.7	1.0	0.15
CG-27	None	13.0	38.0	5.75	-	0.05	1.6	2.5	0.01	0.7	-	38.0	-	-
Inconel 625	None	21.5	61.0	9.0	-	0.05	0.2	0.2	-	-	0.25	2.5	0.2	-
Sanicro 32	None	21.0	31.0	-	3.0	0.09	0.4	0.4	-	-	0.6	42.8	0.6	-
Sanicro 31H	None	21.0	31.0	-	-	0.07	0.3	0.3	-	-	0.6	46.13	0.6	-
12RN72	None	19.0	25.0	1.4	-	0.1	-	0.5	0.06	-	1.8	51.8	0.4	-

TABLE 2-4
RANKING OF CANDIDATE HEATER
TUBE ALLOYS AT 850°C

Alloy	Condition	Stress to Rupture at 3500 hr (MPa)		
		750°C*	850°C*	850°C Lowest Data
CG-27	Solution annealed, precipitation hardened	166.8	51.7	46.7
N-155	Solution annealed	92.9	45.7	30.0
Inconel 625	Solution annealed	131.7	45.3	44.3
Sanicro 32	Brazed, rapidly cooled	**	38.9	31.9
12RN72	Solution annealed	70.0	34.3	32.3
Sanicro 31H	Solution annealed	55.9	32.54	23.9

*Linear regression analysis projection.
**Insufficient data.

because the rings do not seal identically, there is a tendency for the individual working cycles to adopt different mean pressures. To limit the differences to an acceptable level, the four mean pressure tappings are manifolded together. In order to investigate the effect that manifolding might have on engine performance, single piston ring tests were conducted at NASA-Lewis Research Center (NASA-LeRC) on upgraded Mod I Engine No. 10. The tests showed that manifolding the mean pressure tappings did actually limit the mean pressure differences to an acceptable level and that manifolding did not cause any measurable change in engine performance.

Cold Temperature Tests

In order to investigate piston ring sealing at low temperatures, tests were carried out using a motored Mod I engine in a cold room. The tests involved the Mod I BOM split-solid piston rings, Mod II type single solid piston ring, and a single ring with a lap joint. The amplitudes of the cycle pressures generated while driving the engine by the starter were taken as an indication of the quality of the seal provided by the piston rings. As the temperature was reduced, the speed at which the starter motor could drive the engine decreased, but the general conclusion was that the BOM piston rings sealed best and the single rings with a lap joint were second. The results of these tests were fully discussed in the preceding semiannual report (MTI 87ASE555SA11).

Mod II H_2 Leakage

Hydrogen leakage measurements from the Mod II engine crankcase were made over a range of mean pressures (5-15 MPa) and speeds (1000-4000 rpm). Leakage was consistently low (0.26-0.32 cc/min) compared to the dynamic goal of 11.4 cc/min.

Drive System

The major test objective is to obtain 10-hr endurance at maximum pressure to test the integrity of the Mod II engine bottom end; specifically, the Koyo rolling-element bearings. Secondary objectives were to test Mod II single solid piston rings for their tendency to contribute to cycle-to-cycle pressure imbalances, evaluate durability of the hollow rods used with these rings, and prove the acceptability of aluminum-oxide coated coolers.

During this report period, the assembly of the rig and facilities was completed and performance/endurance tests run. The configuration tested included:

- Cast V-block with Koyo bearings
- Aluminum-oxide coated coolers
- Split-solid type piston assemblies
- Oil pump without internal pressure relief.

The water pump and H_2 compressor were not included. Split-solid type piston rods were used because of unsatisfactory fatigue life of the single solid rods.

Initial operation of the rig revealed a misaligned balance weight on the crankshaft. Once corrected, performance tests were conducted at 3, 7, 11, and 15 MPa mean pressures. During these tests, two of the four crossheads galled in the block. As a result, the cast block was sleeved with type A cast-iron crosshead liners and the crosshead clearances increased to 0.05-0.06 mm. These tolerances and the use of a sleeve are consistent with the Mod II engine analog block. It had been hoped that the increased lubricity of the cast block material, compared to the stainless steel analog block, would be sufficient to prevent wear and galling.

After reassembly, the performance and 10-hr maximum power endurance tests were completed. Inspection revealed that the Koyo bearings and aluminum-oxide coolers were in excellent condition. Damage was sustained to the oil and water pumps. In the first instance, a worn bushing is attributed to lack of internal pressure relief, which will be corrected on the engine. The failed water pump bearing is the result of not having a complete water pump.

During the next report period, testing will be conducted to evaluate the internal pressure relief oil pump, reduced water pump friction, and determine the performance benefits of single solid piston rings and reduced dead volume.

Control System/Auxiliaries Development

The major goals of this task are the development of the engine control and auxiliaries systems. Specific systems goals include the development of a highly flexible DAFC with low combustion air pressure drop and low idle fuel consumption, a simplified MPC that does not require a servo-oil actuator, a high-efficiency combustion air blower and electric drive system, and logic to operate various control systems.

Throughout the semiannual report period, emphasis was placed on testing, debugging, and final development of the various Mod II control systems. Bench tests, the Mod II engine, and the Spirit vehicle (particularly the latter) were used to achieve functional optimized systems for use in the Mod II cell and Celebrity vehicle during the remainder of the program.

Combustion Control

Early in the report period, modifications were made to the hardware and software to increase the lambda resolution and add a self-calibration feature at low fuel flows. These modifications were installed in the Mod II test cell and Spirit vehicle and were successful in allowing smooth transition from high (used at low fuel flows) to normal gain, as well as excellent control to fuel flows as low as 0.17 g/sec, the Mod II idle goal.

Transient tests in the Spirit vehicle* revealed that the electronic driving circuit for the pulse width modulated (PWM) metering valves, as well as the ΔP regulator, were affected by ambient temperature, resulting in a shift in lambda. Military specification electronic components were utilized to correct the problem.

The Spirit vehicle tests also revealed that excessive soot levels were occurring during decelerations and at some steady-state conditions. Soot is of concern because of preheater plugging (reduced engine efficiency) and particulate emissions. The excessive soot on deceleration was found to occur because of a 0.25-sec time lag introduced by a digital filter used on the Hitachi airflow meter. The purpose of the filter was to remove spurious high-frequency noise generated by air turbulence in the flow meter, which interfered with the DAFC. The result was that during deceleration, lambda decreased to levels where soot was generated due to over-rich combustion.

The addition of an anticipatory algorithm, based on engine or blower speed, was proposed to compensate for the built-in time lag between air and fuel flow output signals. This algorithm, however, was not needed once an 8-Hz breakpoint analog filter was added and the breakpoint of the digital filter was increased from 0.71 to 5 Hz. The latter change substantially reduced the time lag between actual and indicated airflow and reduced soot by an order of magnitude during deceleration to acceptable levels.

As a result of the Spirit evaluation, the operation of the DAFC in a vehicle environment is known. Other observations were the regulated pressure differential across the fuel metering injectors fluctuated as much as ±7 psi around the

*Mod II SES installed on an upgraded Mod I engine, see "Spirit Vehicle" for full description.

15-psid mean value, the existence of a pulsating flame at high atomizing airflows, possible cavitations in the fuel pump, a tendency of the system to drift out of calibration in relatively short periods of time, and sensitivity to soot if atomizing airflow is less than the required 1.0 g/sec.

The pressure variations, pulsating flame, and cavitation do not impact the performance of the system. Extending calibration intervals and ensuring adequate atomizing airflow will be addressed during the next report period. It can be concluded that the current DAFC produces stable lambda control and low soot levels when properly calibrated and supplied with sufficient atomizing air.

In order to improve the DAFC, an advanced system has been designed using a standard automotive, off-the-shelf Bosch ΔP regulator, Ford fuel injector, and Walbro pump (Figure 2-21). This system will operate at higher pressure, use a single (versus the current two) injector, modified drive electronics, and current-driven injectors. Greater accuracy, reliability, and low fuel flow operation control are anticipated. Development and incorporation into the Mod II will occur in the next report period.

The Gast Roc-R atomizing air compressor selected for the Mod II was subjected to a 500-hr endurance test using a 12.5-min-on/2.5-min-off cycle, resulting in 2000 start/stops. The test was successfully completed with a dc motor brush length reduction of 28%. Durability problems with this compressor during the NASA TU program are attributed to high under-hood temperatures and/or low voltage.

As a result of the change to the 3-hole conical fuel nozzle, increased atomizing airflow and pressure are required. These higher levels (1 g/sec at 20 psid) cannot be met with the Gast compressor at the manufacturer's rated conditions. Attempts to provide the higher flow by supplying 13.5 V to the 12-V motor result in airflow decreasing from 1.0 to 0.8 g/sec after only a few hours. A temporary solution was to remove all inlet restrictions and drive the compressor at 2300 rpm versus the rated 2100 rpm. Although the required flow is provided (Figure 2-22), power requirements are excessive. During the next report period, a Gast compressor with three inlet and three outlet ports will be evaluated as a replacement.

Control System Analysis

A remote DEC monitor system was completed, which allows control variables of an engine operating in the field to be monitored and changed using modems over public telephone lines. This system was used to support the NASA TU vehicle at Langley Air Force Base.

Algorithm and software development for the Mod II 3-volume compressor, start/stop sequencing, low idle control, and temperature control continued. Included was an extensive review of the DAFC and blower control logic to improve the operation of the combustion control system.

Upgraded DEC

The objectives of upgrading the DEC are to provide low-temperature capability (-40°C), reduce the amount of time it takes with the current DEC to implement software changes, and use of low-cost, off-the-shelf components.

Preliminary hardware design was initiated. The present design consists of ~75% off-the-shelf stock purchased and ~25% MTI-designed and manufactured printed circuit boards. All off-the-shelf hardware has been identified, purchased, and is presently fully operational. Detailed design of MTI-designed and manufactured hardware was initiated.

Detailed software specifications were completed and released. Software design and coding, based on the software specifications, were initiated. Software development is approximately 30-40%

completed. Functions completely coded and tested include the real-time operating system, digital input/output interface, DAFC logic, all auxiliaries, and the monitor communication logic. Documentation for all software currently in place has been completed.

The monitor hardware has been specified, purchased, and is currently operational. The engine control monitor hardware consists of an off-the-shelf IBM PC compatible portable lap-top computer. The monitor software is ~90% completed for a minimal functionality that replicates present DEC monitor functionality. As designed, the monitor and engine control are operating as a unit.

All development tools required for upgraded DEC software development have been purchased and are fully operational. These tools include software compilers, assemblers, and the microprocessor emulator.

Mean Pressure Control (MPC)

Spirit vehicle testing of the Mod II 3-volume compressor and the two-tank hydrogen system was completed. Initial Spirit tests compared urban CVS cycle performance where the Mod II pressure response (Figure 2-23) demonstrated an improvement over that of the upgraded Mod I (Figure 2-24). Tests to evaluate whether two or three compressor volumes are needed demonstrated a slight mileage improvement with three volumes (Table 2-5). Since this mileage improvement was projected to grow to 0.5 mpg in the Mod II Celebrity and drivability was improved, it was decided to use all three volumes.

Rig performance tests of the 3-volume hydrogen compressor indicated round pumping losses less than projections (Figure 2-25). Other performance data are illustrated in Figures 2-26 through 2-28. A 500-hr rig endurance test was also completed (Figure 2-29) with no unusual wear found after the test.

TABLE 2-5
SPIRIT MILEAGE RESULTS
3-VOLUME COMPRESSOR

EPA Driving Cycle	Fuel Economy (mpg) (σ = Standard Deviation) Five Modes (3 Volumes)	Three Modes (2 volumes)
HWFET	42.12 (σ = 0.26) (7 Data Pts.)	41.97 (σ = 0.33) (6 Data Pts.)
Phase I Urban	30.26 mpg (σ = 0.64) (21 Data Pts.)	30.14 mpg (σ = 0.58) (16 Data Pts.)
Phase II Urban	26.80 (σ = 0.71) (11 Data Pts.)	26.79 (σ = 0.54) (12 Data Pts.)

Other MPC activities included modifying the electric-driven circuit for the five solenoid valves in the Mod II system. This was successful in reducing a continuous 35 W-per-valve current down to 8 W per valve. This was achieved by providing an initial current of 2.5 amperes to open the valve and then reducing it to 0.6 amperes to hold the valve open. A substantial improvement in Celebrity mileage is expected as a result.

It is concluded that the Mod II MPC system, including power control valve, 3-volume compressor, and the two-tank system, is functional and reliable. At the close of this report period, the system is being installed in the Mod II engine for optimization and tuning tests.

Auxiliary Development

Mod II Combustion Air Blower

Blower development concentrated on correcting excessive impeller-to-shroud clearances that resulted from manufacturing errors, evaluating performance, and making design modifications to allow nondestructive disassembly of the impeller from the shaft.

The excessive clearance was corrected by applying an 0.007-in. thick abradable Teflon coating to the housing. Although this was successful in reducing the impeller-to-shroud clearance to less than 0.001 in. at the impeller exit, the clearance increased along the contour and was 0.025-0.030 in. at the inlet. This will be corrected by machining new housings of the proper contour.

The performance of the Teflon-coated blower was determined from bench tests (Figure 2-30). In order to meet the Mod II design point, a slightly higher than intended blower speed (38,000 rpm) is required. Measured overall efficiency varied between 56 and 63% (Table 2-6). Included in this are aerodynamic efficiency (impeller and volute) as well as shaft bearing, rotor windage, and eddy-current losses produced by the permanent magnet motor rotor. The corresponding design point aerodynamic efficiency of 79%, slightly less than the design goal of 83%. Reducing the impeller-to-shroud clearance is anticipated to increase efficiency to the design goal.

TABLE 2-6
MOD II BLOWER
MAXIMUM MEASURED EFFICIENCY

Blower (rpm)	ΔP (H_2O)	Mass Flow (g/sec)	Efficiency* (%)
16,000	14.8	53.3	56
20,000	24.0	65.7	62
24,000	34.7	78.4	63
28,000	46.9	93.2	64
32,000	63.3	104.8	63
36,000	82.3	118.5	63
39,150	98.0	112.2	63

*Air hp out/hp in.

The method of mounting the aluminum impeller on the stainless steel motor shaft was changed after it was found that a heavy interference fit over the entire length of engagement made disassembly virtually impossible. The improved method provided reduced shrink fit and provisions for hydraulic removal of the impeller from the shaft (Figure 2-31). The validity of this concept for allowing easy removal of the impeller was demonstrated first with a model and later with actual blower parts.

Mod II Blower Drive System

The development of the blower drive system made extensive use of bench and Spirit vehicle tests. A performance test of the entire blower drive from simulated engine shaft power in to airflow out was conducted on the bench (Figure 2-32). Measured power and efficiency at various locations in the system are given in Figures 2-33 and 2-34. The peak efficiency of 37% was substantially below the goal of 68%. A second set of efficiency data was obtained at a constant alternator speed of 10,000 rpm, using PWM regulation to vary blower speed (Figure 2-35). In this case, efficiency degrades sharply with speed due to poor wave form factor at the 6.7-kHz PWM frequency used for these tests.

In order to improve efficiency (form factor), PWM frequency was increased to 15 kHz and transient evaluations were conducted using the Spirit vehicle. During the initial CVS cycle tests with a Mod I blower (all other drive system components were Mod II) it was found that the blower could not keep up with demand. Increasing the current limit improved the lag but resulted in power transistor failure during 0-60 mph accelerations. A number of changes were tried to prevent power transistor failure during or slightly after hard acceleration. These included substituting 100-A for 50-A transistors, installing capacitors to limit voltage spikes, reducing current limit setting, current limiting with linear proportioning feedback, and installing a Mod II blower/motor. These modifications were unsuccessful.

The course of transistor failure was traced to the change to 15-kHz PWM frequency with the aid of strip-chart recordings. Manufacturer specification indicates that the transistors should operate in the linear (on/off) region 1% or less of the time, because of the high losses that occur when switching generates heat that is detrimental to transistor life. Test data indicated the blower drive system was in the linear region 10% of the time. Returning to the reduced efficiency of 6.7 kHz, frequency results in transistors operating in the linear region 3% of the time (i.e., long-term reliability may be questionable).

Given the unsatisfactory reliability of the existing 15-kHz PWM-based system, several alterations were considered:

1. Retain 15-kHz PWM but use transistors with faster switching characteristics
2. Retain PWM but reduce frequency to 1.4 kHz, thereby obtaining 1% linear region operation
3. Retain PWM but reduce frequency to 6.7 kHz
4. Mechanical drive
5. Eliminate PWM and go to a conventional automotive field-regulated alternator.

The first option was rejected because the transistors are difficult to obtain at the required current rating and are not in general commercial use. The second would result in unacceptable efficiency, while the fourth presents packaging problems and represents long development time. The conventional alternator approach was selected because it retains many of the existing system components (Figure 2-36), utilizes a conventional off-the-shelf alternator, and is estimated to have efficiency better than the 6.7-kHz PWM system (Table 2-7). PWM is retained for start-up and a second conventional alternator is used for battery charging thus eliminating the battery charge system. The 6.7-kHz PWM system will also be developed as a backup.

TABLE 2-7
COMPARISON OF ORIGINAL PWM AND FIELD-REGULATED BLOWER DRIVE SYSTEM POWER (W)

	PWM	Field Regulated
CVS Cycle Average Operating Point (1200 rpm, 7 MPa)	400	400
Maximum Power (4000 rpm, 15 MPa)	5000	3069

Bench tests of the field-regulated alternator have begun and will be completed using the Spirit vehicle and Mod II during the next report period.

Mod II Battery Charge System

Bench tests were used to develop the battery charge system electronics and to evaluate performance. Several over temperature induced failures were encountered resulting in modifications to increase heat sinking and cooling, reduce wire lengths, and use higher rated components. After modification, the system proved capable of surviving operation up to 20,000 alternator rpm and 65-A output. Maximum current output was 87 amperes obtained at 15,000 rpm. Average system efficiency was 60% (Figure 2-37).

A 100-hr endurance test of the system was completed during the test setup illustrated in Figure 2-38. The steady-state test was run at 10,000 alternator rpm and a load of 60 amperes. This test, however, did not exercise the relays that select series or parallel winding connections at 6000-8000 rpm.

The final test series was conducted in the Spirit vehicle where transient durability could be assessed. Initial operation revealed that a high level of electrical and electromagnetic noise was interfering with the DEC causing it to trip off repeatedly. The prototype Mod II system was substituted, and its different packaging eliminated noise interference with the DEC. The cause for the original interference was not determined initially because the Spirit was used to evaluate the blower drive system and finally because of the decision to go to a conventional blower and battery charge system.

A conventional automotive Delco alternator will now be used for battery charging. The alternator will be located colinear and coupled to the blower drive alternator.

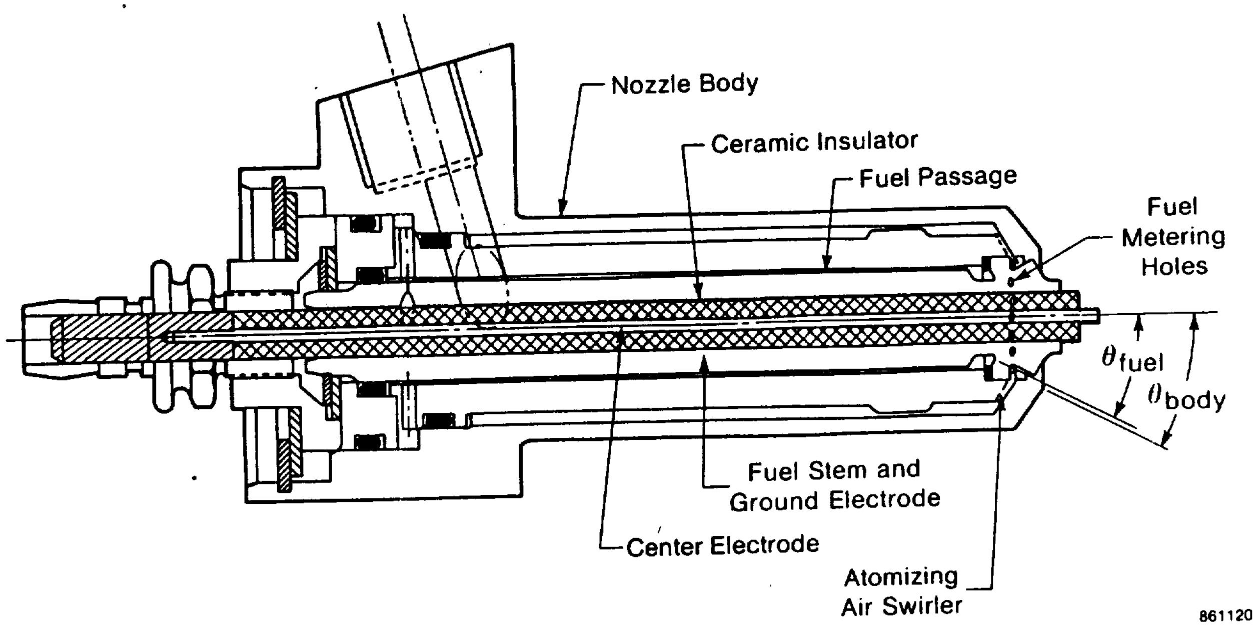


Fig. 2-1 Center Igniter Conical Nozzle

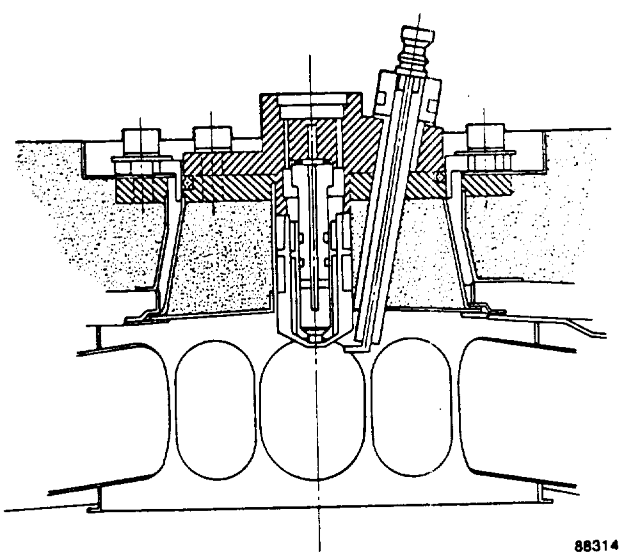


Fig. 2-2 Integral Igniter Conical Nozzle and Nonbellows Seal CGR Combustor

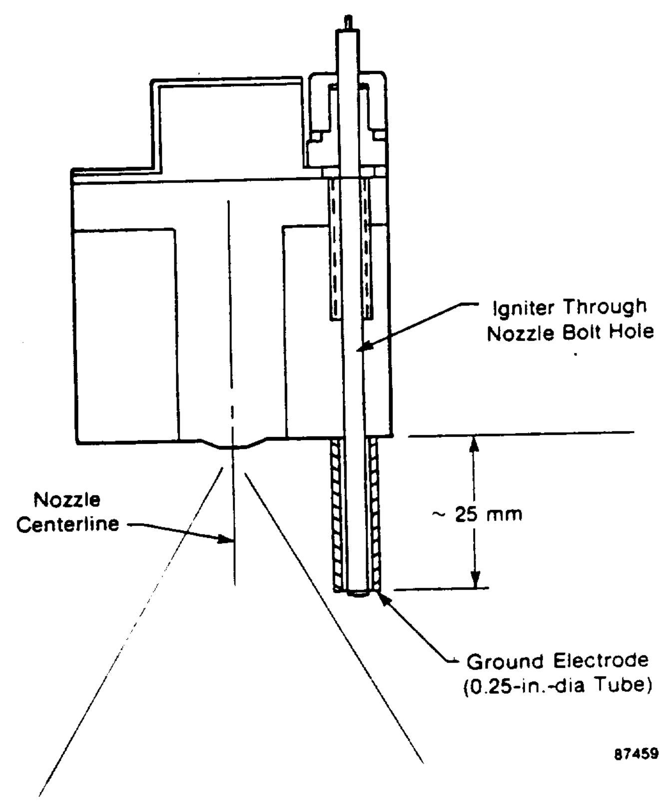


Fig. 2-3 Parallel (Side) Igniter 3-Hole Conical Nozzle

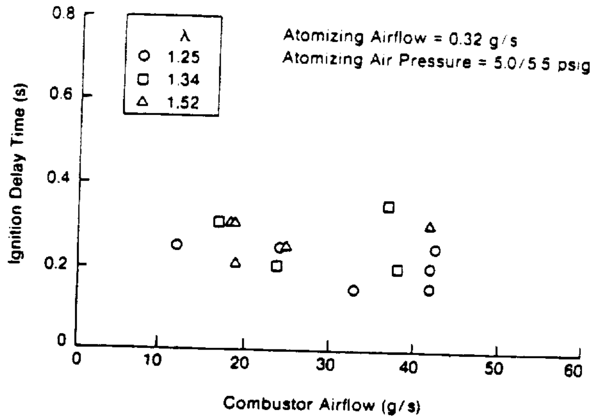


Fig. 2-4 Angled Side Igniter 3-Hole Conical Nozzle Ignition Delay Times (19-mm Insertion) in Spirit Vehicle

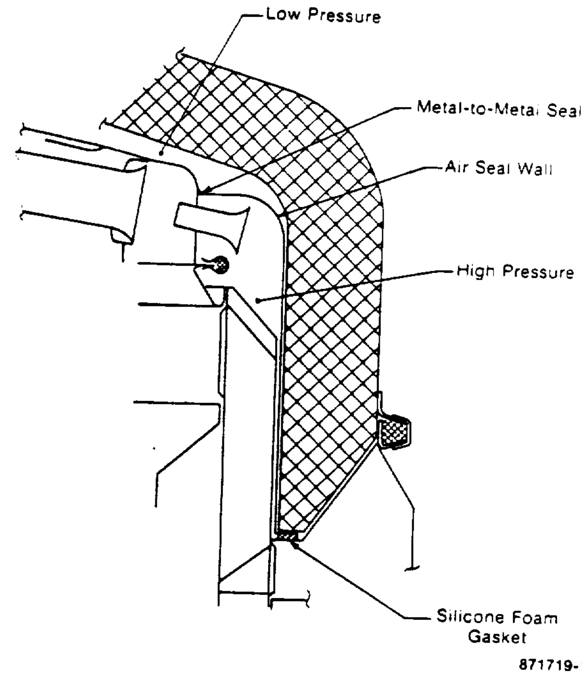


Fig. 2-6 Mod II Sealed CGR Combustor

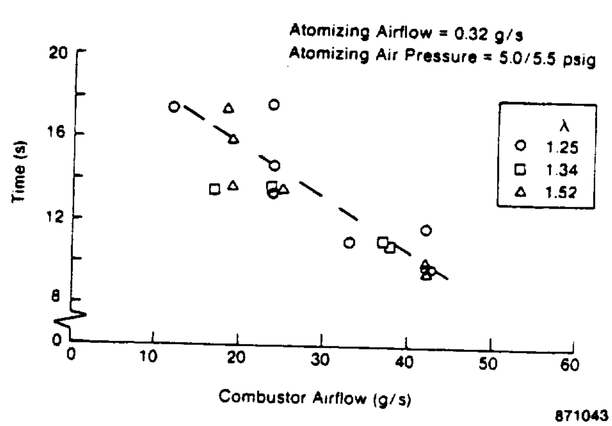


Fig. 2-5 Angled Side Igniter 3-Hole Conical Nozzle Time to Achieve Indicated 50°C Tube Temperature Rise in Spirit Vehicle (19-mm Insertion)

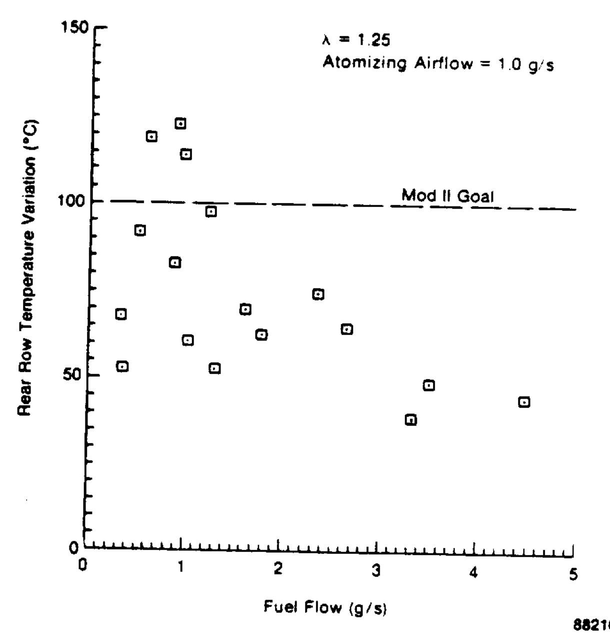


Fig. 2-7 Mod II Engine Rear Row Heater Head Temperature Variation

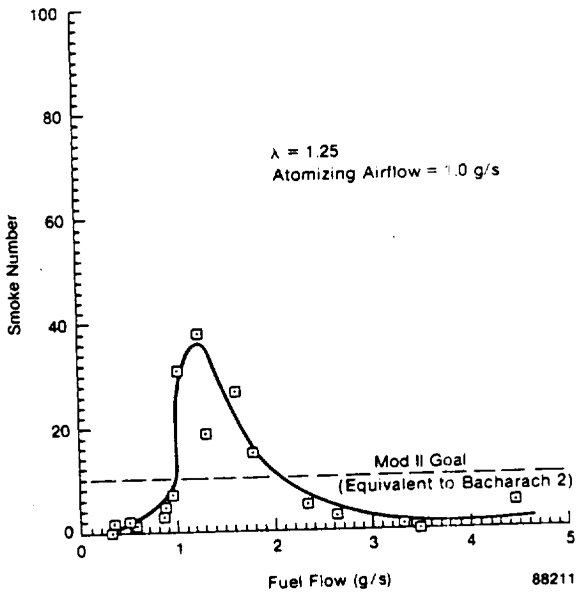


Fig. 2-8 Mod II Engine Soot Emissions

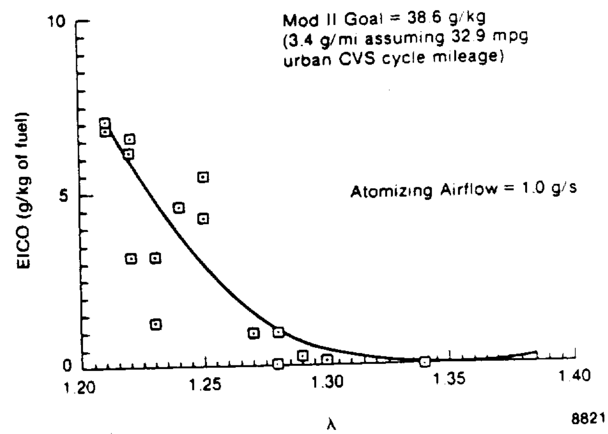


Fig. 2-10 Mod II Engine CO Emissions

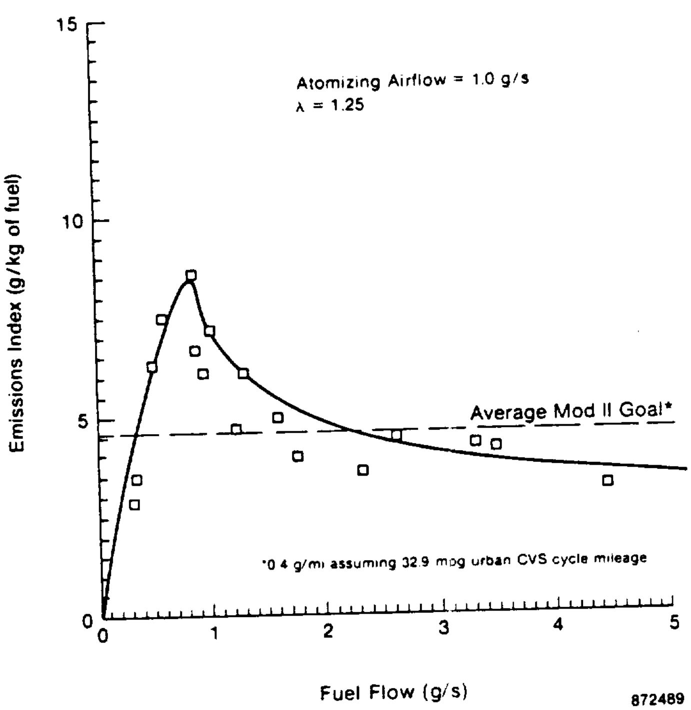


Fig. 2-9 Mod II Engine NO_X Emissions

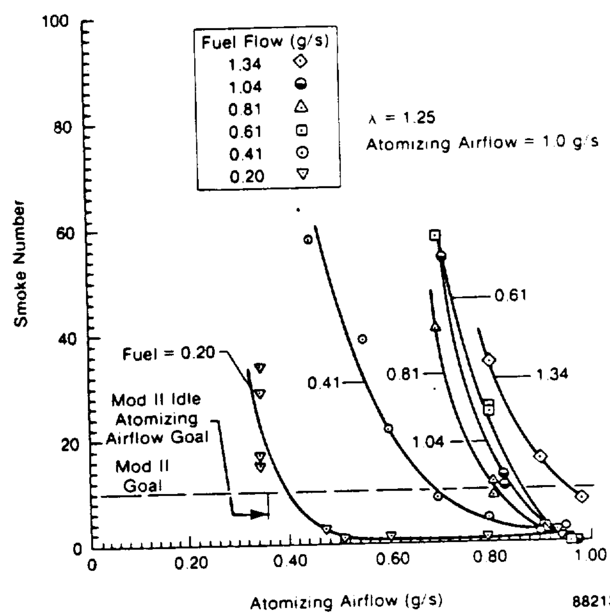


Fig. 2-11 Effect of Atomizing Airflow on Mod II Engine Soot Emissions

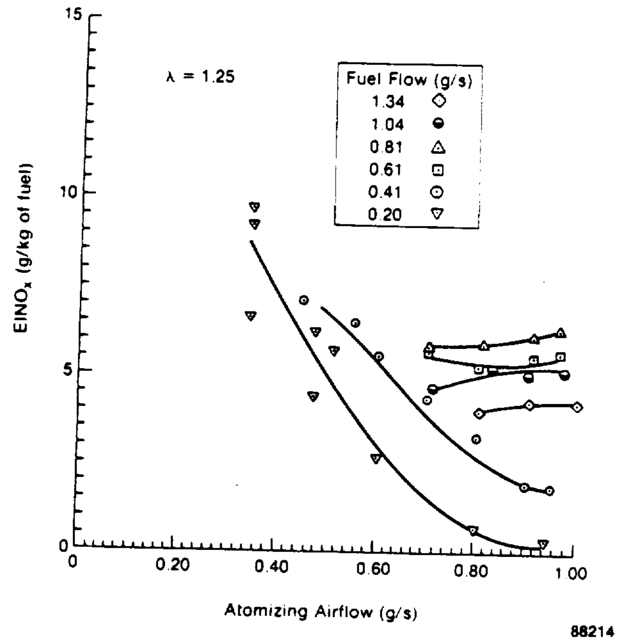


Fig. 2-12 Effect of Atomizing Airflow on Mod II Engine NO_x Emissions

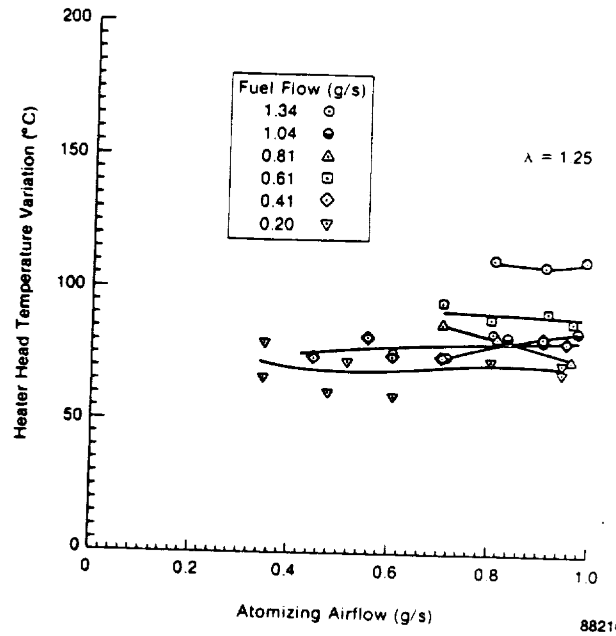


Fig. 2-14 Effect of Atomizing Airflow on Mod II Heater Head Temperature Variation

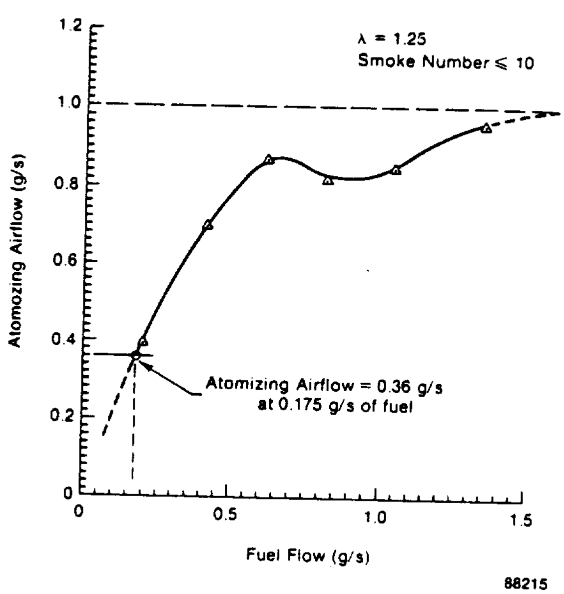


Fig. 2-13 Minimum Mod II Atomizing Airflow Requirement

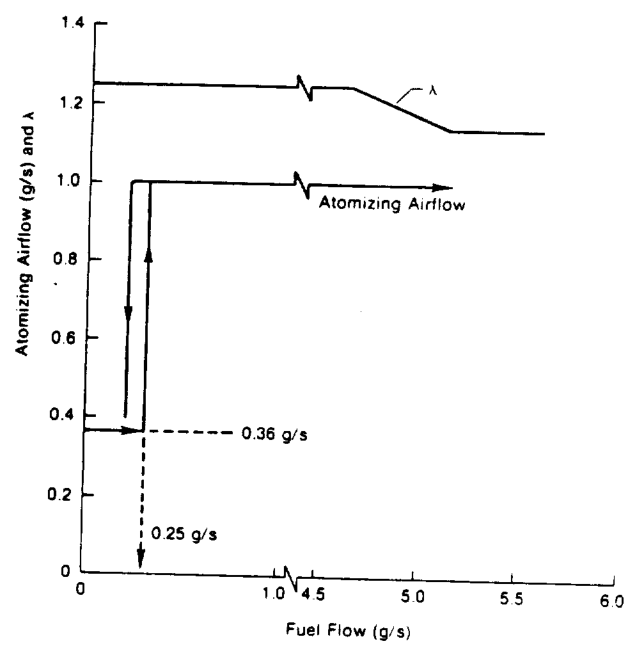


Fig. 2-15 Mod II Vehicle Atomizing Airflow and Lambda Schedule

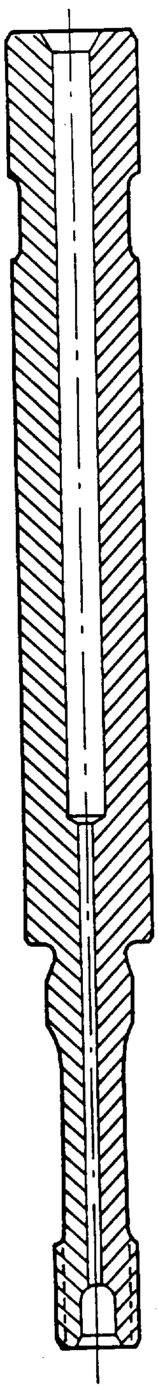


Fig. 2-16 Single Solid Piston Ring Rod Cross Section

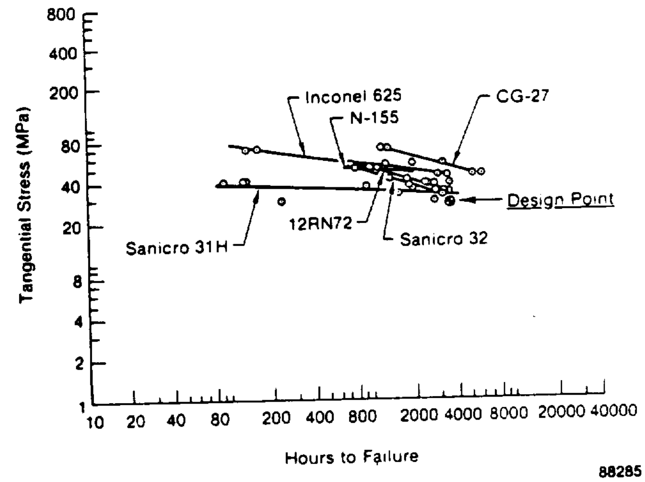


Fig. 2-17 Heater Tube Creep Rupture at 850°C

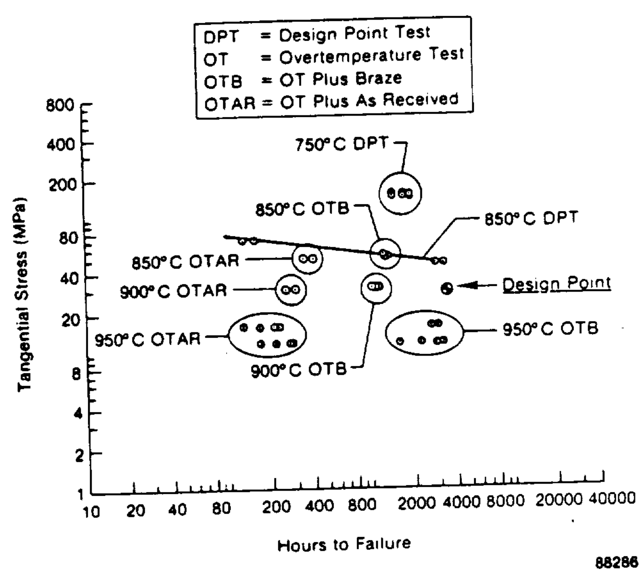


Fig. 2-18 Inconel 625 Creep Rupture at Design and Elevated Temperatures

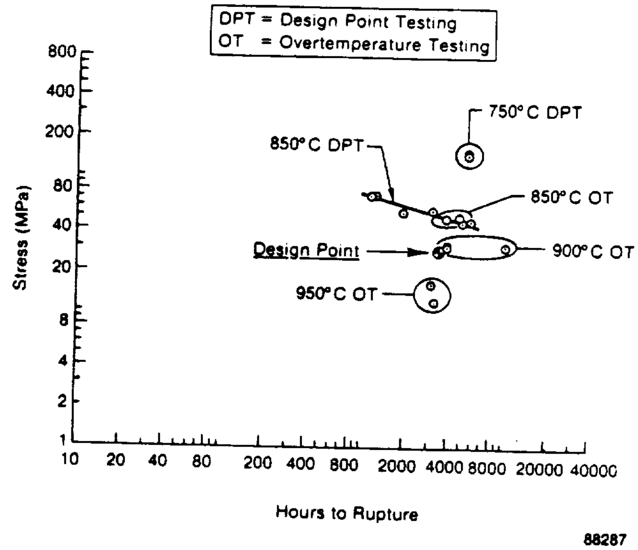


Fig. 2-19 CG-27 Creep Rupture at Design and Elevated Temperatures

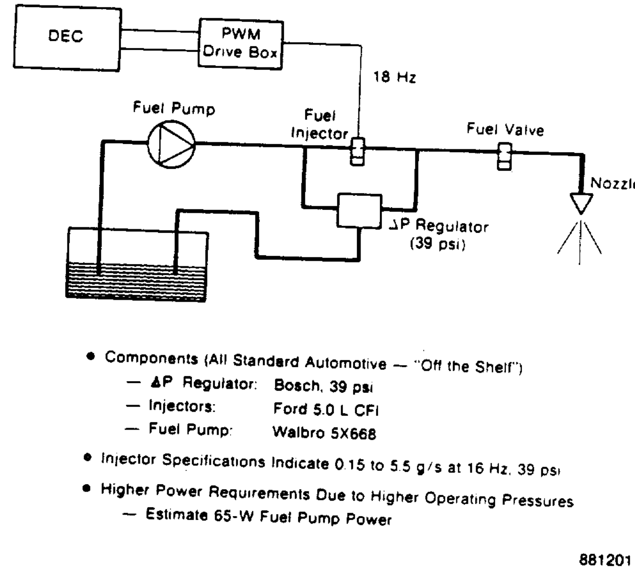


Fig. 2-21 Advanced DAFC

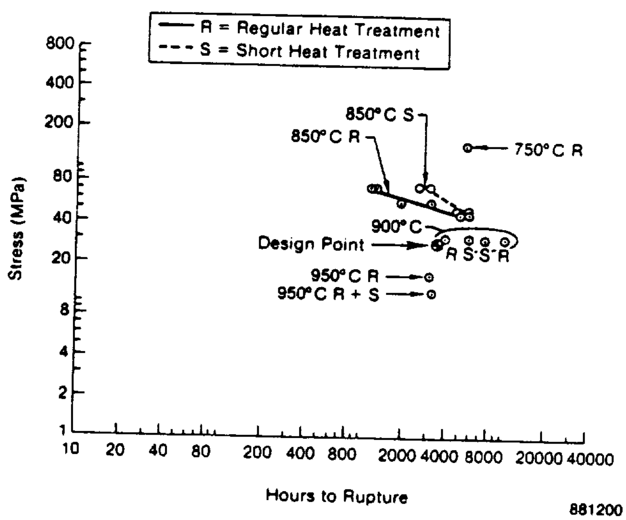


Fig. 2-20 Effect of Heat Treatment on CG-27 Creep Rupture

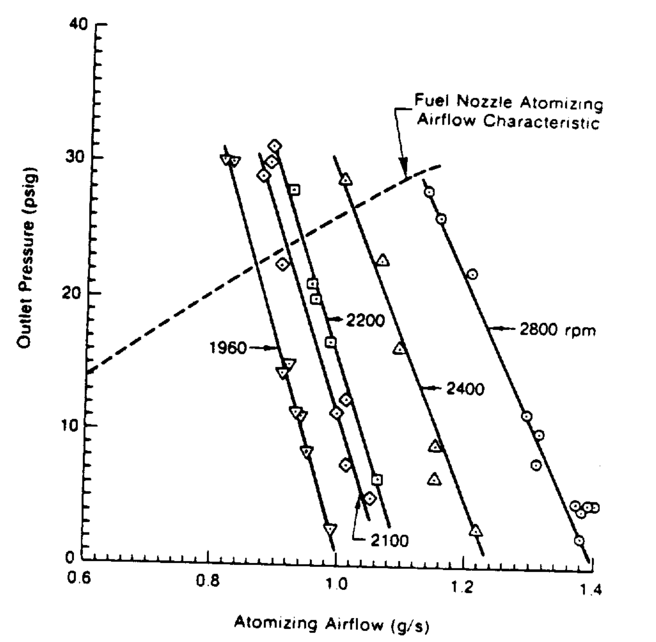


Fig. 2-22 Gast Roc-R Compressor Performance without Inlet Restriction

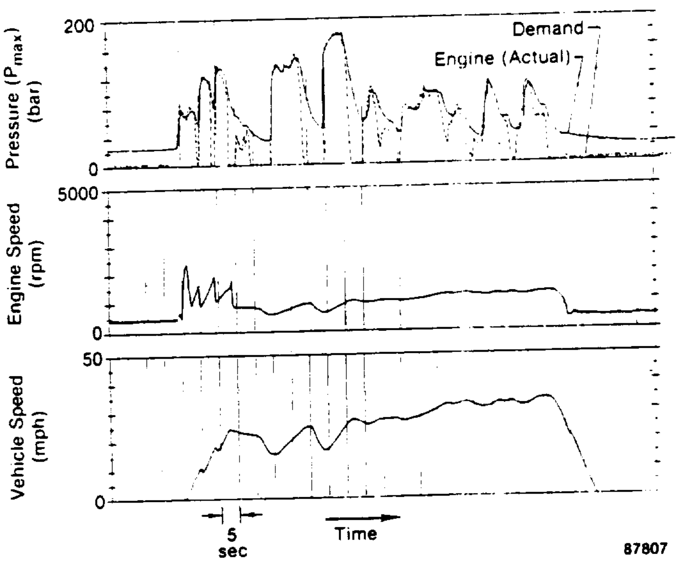


Fig. 2-23 Spirit Vehicle Performance over First Cycle of EPA Urban Driving Cycle with Upgraded Mod I MPC System

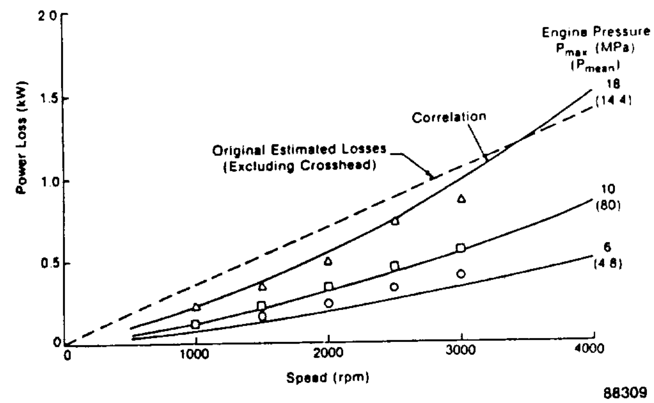


Fig. 2-25 Mod II 3-Volume Compressor Round-Pumping Power (Including Crosshead Losses)

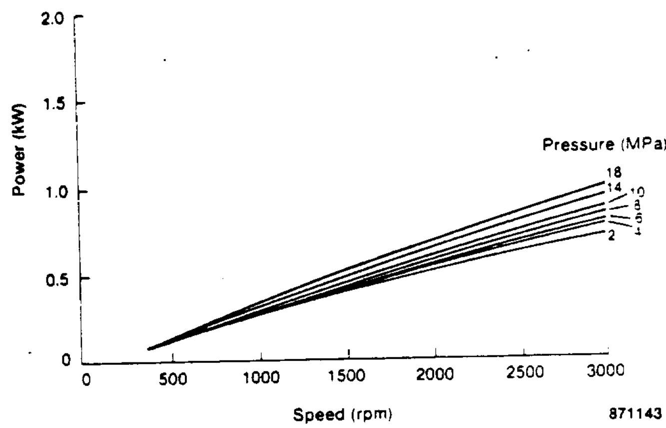


Fig. 2-26 Mod II Compressor Losses with All Pistons and Capseals Removed

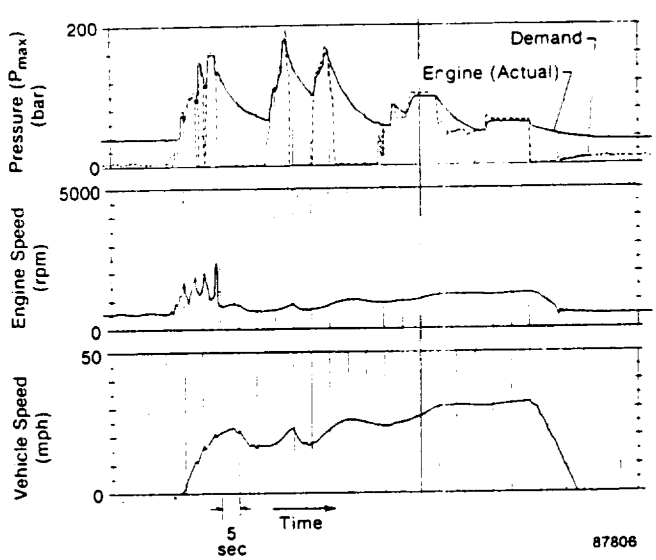


Fig. 2-24 Spirit Vehicle Performance over First Cycle of EPA Urban Driving Cycle with Upgraded Mod I MPC System

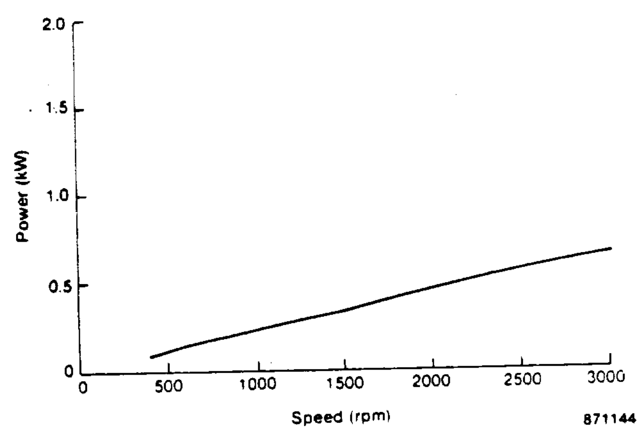


Fig. 2-27 Mod II Compressor Crankcase Losses — Crankshaft, Connecting Rod, and Crosshead

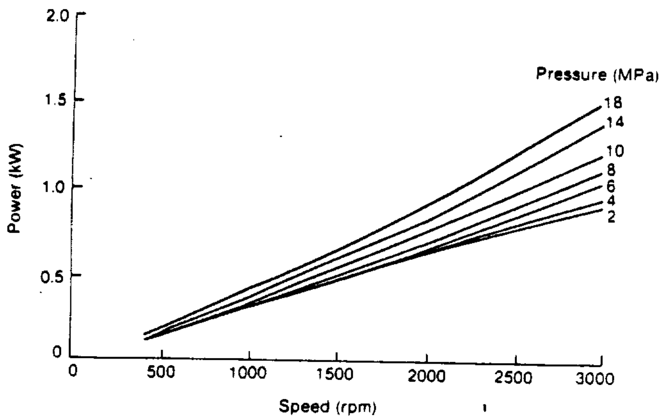


Fig. 2-28 Mod II 3-Volume Compressor Power Loss at Round Pumping — All Volumes Engaged

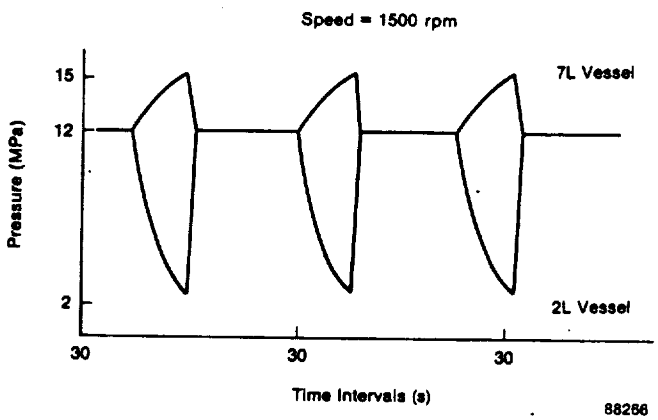


Fig. 2-29 Mod II H_2 Compressor Endurance Cycle

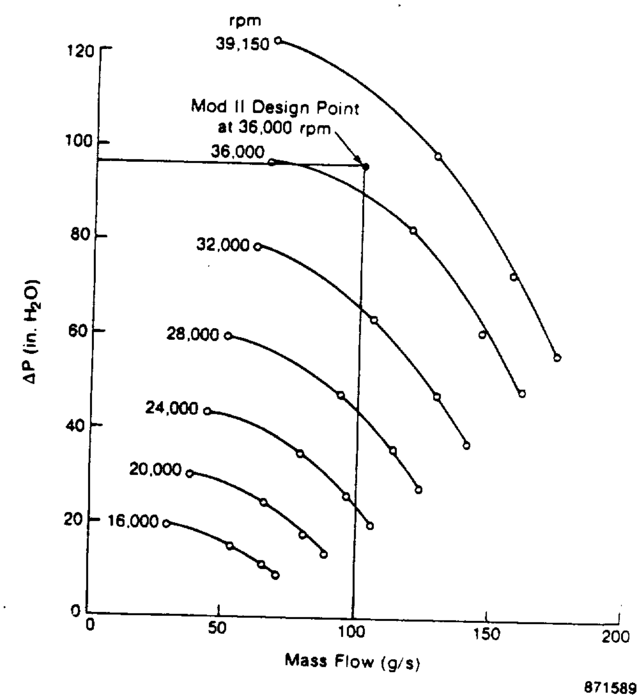
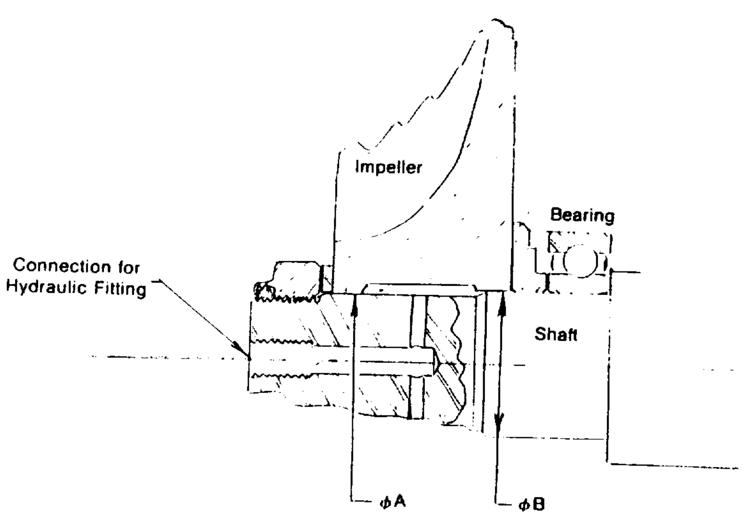


Fig. 2-30 Mod II Combustion Blower Map with PTFE (Teflon) Coating



$\phi A > \phi B$

- Therefore, Impeller Assembles Freely onto Shaft Except for Last 3 mm of Engagement
- Assembly Is Made by Heating Impeller to 300°F, Which Is Sufficient to Make a Loose Fit at the Two Pilots
- Disassembly Is Done By Hydraulic Pressure, Which Expands Impeller Bore. Also Differential Area Between ϕA and ϕB Produces Hydraulic Pressure to Push Impeller Axially Off Shaft

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Fig. 2-31 Mod II Blower Impeller/Shaft Fit Design to Facilitate Disassembly

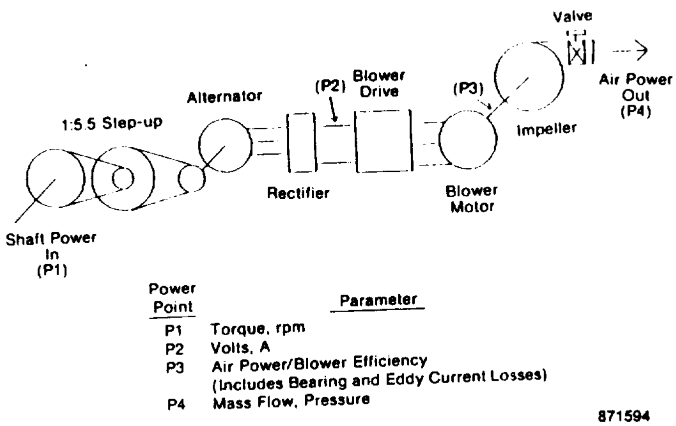

Fig. 2-32 **Blower System Efficiency Test Setup**

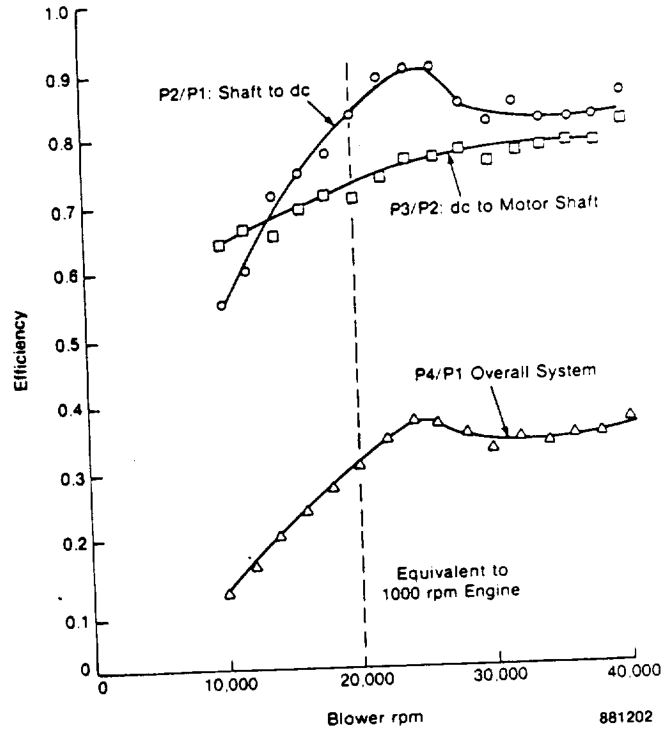

Fig. 2-34 Mod II Blower Drive Subsystem Efficiencies

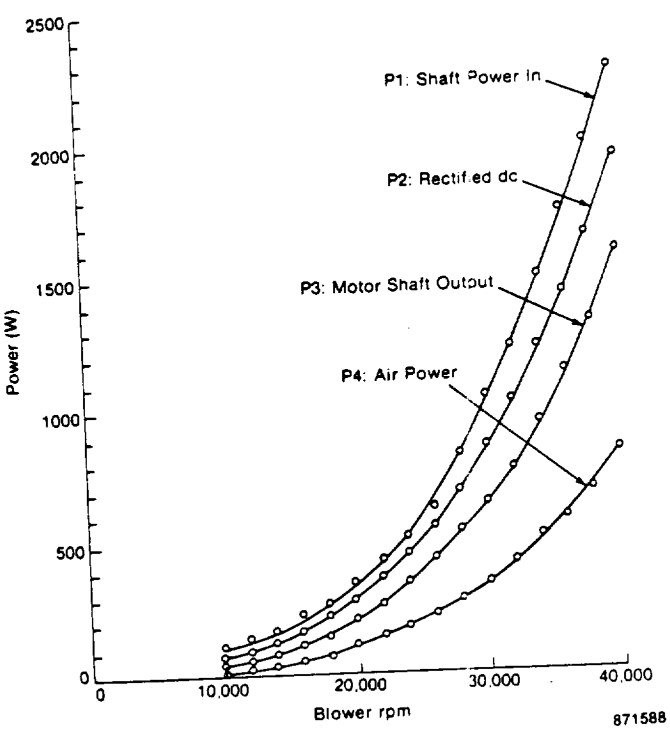

Fig. 2-33 Mod II Blower Drive System Power

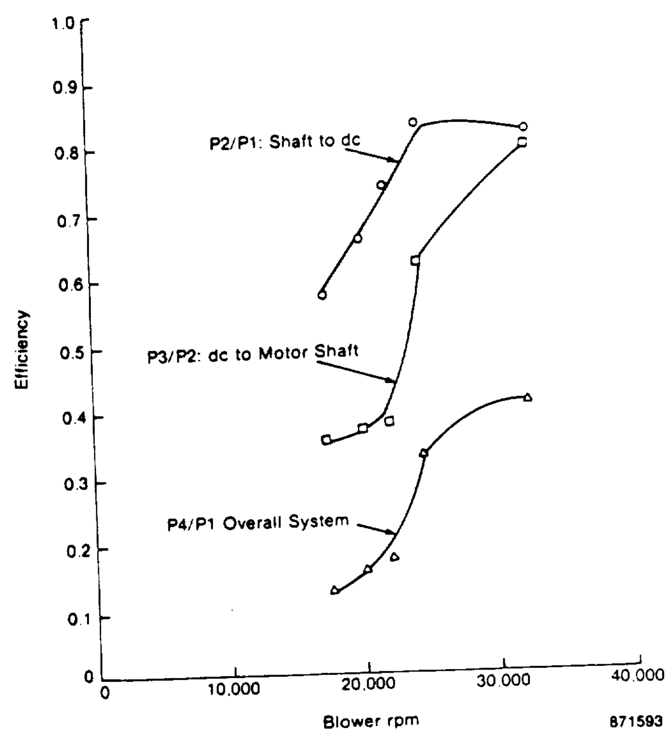

Fig. 2-35 Mod II Blower Drive System Efficiency with 6.7 kHz PWM Blower Regulation (Constant 10,000-rpm Alternator)

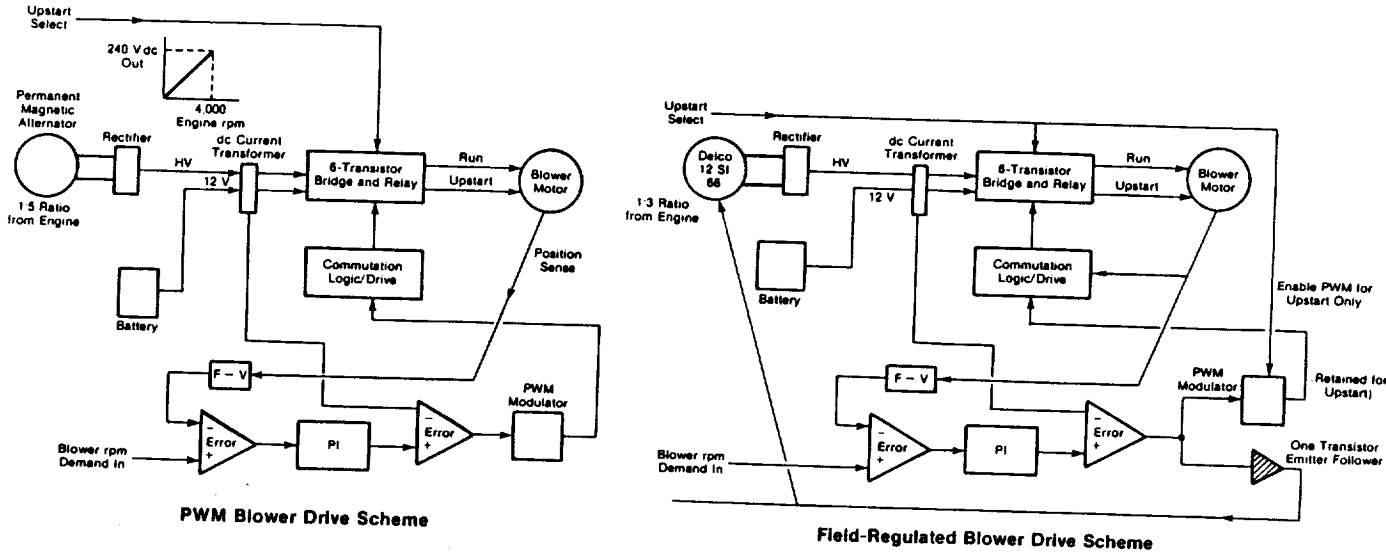

Fig. 2-36 Mod II Blower Drive Schematics

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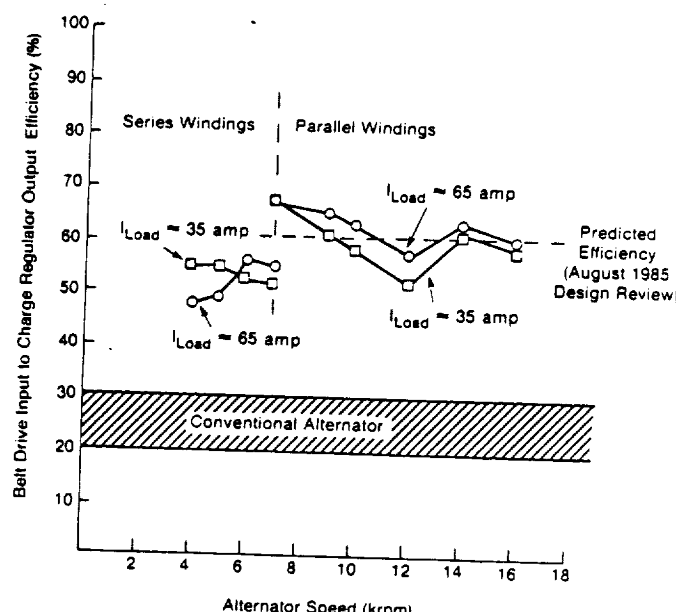

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2-37 Prototype Mod II Battery Charge System Efficiency

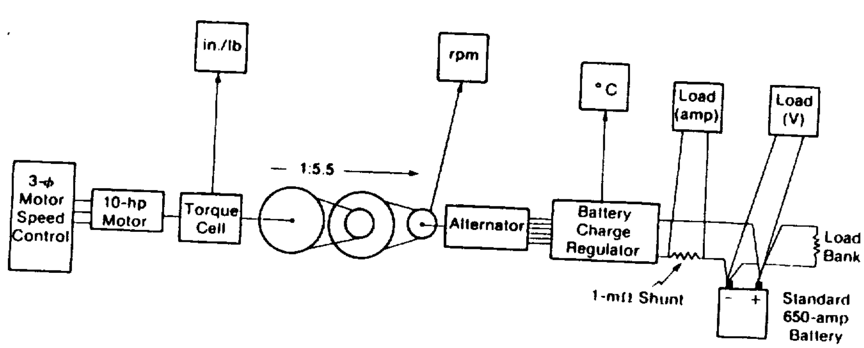

Fig. 2-38 Battery Charge Regulator Test Setup

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III. MOD I ENGINE DEVELOPMENT

Mod I Hardware Development

During the first half of 1987, the Mod I engines still in the ASE program were devoted to the development of technologies related strictly to the Mod II engine program or as prime movers for the NASA technology utilization program. The major efforts on the Mod I program were:

- Mod II controls and auxiliaries evaluation
  - DAFC
  - Electric PCV
  - Electric blower
  - Blower drive system
  - Battery charge circuit
  - Two-tank H_2 system
  - 3-volume H_2 compressor
  - DEC
  - Atomizing air compressor
- Reliability and durability improvements
  - Atomizing air compressor
  - Combustors
  - DEC
  - Instrumentation
  - Auxiliaries.

Mod I Engine Test Program

During this semiannual report period, a total of five upgraded Mod I engines were operational at one time or another. Four engines were located in the United States at MTI, NASA-LeRC, and Langley Air Force Base, and one in Sweden at USAB. The specific purpose of each engine is listed below:

- Engine No. 5 (Langley Air Force Base) - installed in the Air Force Phase I van
- Engine No. 8 (MTI) - Spirit vehicle
- Engine No. 9 (MTI) - installed in the Air Force Phase II pickup truck
- Engine No. 10 (NASA) - single solid and hot piston ring evaluation
- Engine No. 11 (USAB) - upgraded from Mod I engine No. 3.

The following is an itemized account of the activities of the program engines. During this period, an additional 1247 hours were accumulated bringing the program total engine hours to 17,835 (Figure 3-1).*

Upgraded Mod I Engine No. 5

Engine No. 5 accumulated a total of 853 hours of operation during the first half of 1987 bringing its total operational hours to 2848. During this period, the engine was installed in a step van operating at Langley Air Force Base. At the completion of testing on unleaded gasoline, JP-4, and diesel, the van was shipped to Deere and Company in Moline, Illinois, for interplant mail service. Details are given in Section VI, Technical Assistance.

Upgraded Mod I Engine No. 8

Engine No. 8 at MTI is located in the Spirit vehicle. During the first half of 1987, the engine accumulated 212 hours and 2585 miles bringing its total to 1429 hours and 13,763 miles (Figure 3-2). During this period, the engine was assigned to component development for transient evaluation of Mod II hardware. The following Mod II components were evaluated:

- 3-hole conical nozzle
- CGR combustor

*Figures at end of this section, beginning on page 3-3.

- DAFC
- DEC
- MPC
  - Power control valve
  - 3-volume/2-volume hydrogen compressor
  - Two-tank system
- Atomizing air compressor
- Blower drive system
  - Alternator
  - Electronics
  - Motor
  - Blower
- Battery charge system
  - Electronics.

The test cycle consisted of repeated start-ups, shutdowns, 0-60 mph accelerations, and CVS cycles. A total of 117 hours, 1382 miles, and 101 starts were achieved using this durability test cycle before termination in June so that resources could be devoted to the Mod II Celebrity. Details of the results obtained on the chassis dynamometer are contained in Section II under "External Heat System Development" and "Controls System/Auxiliaries Development."

Upgraded Mod I Engine No. 9

Engine No. 9 is located in an Air Force pickup truck. It accumulated a total of 21 hours during the first half of 1987 bringing its total operational hours to 414. This small number of hours was accumulated during performance testing prior to installation in the truck. The results of the test, performed at NASA-LeRC, indicated performance comparable to earlier builds, Figure 3-3. The truck will become operational in August and shipped to Langley Air Force Base for evaluation. Details are given in Section VI, Technical Assistance.

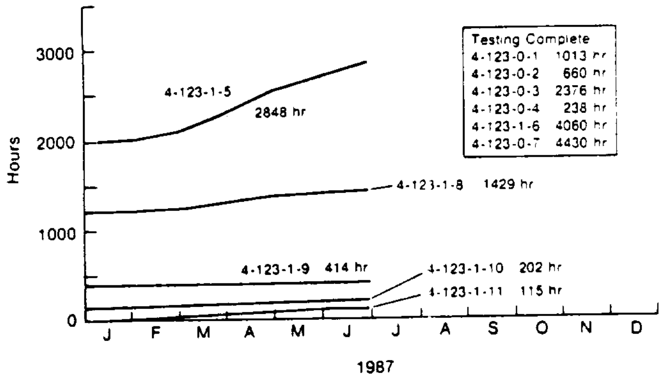
Upgraded Mod I Engine No. 10

Engine No. 10 is located at NASA-LeRC where tests were conducted to evaluate the effect of piston ring design on performance. A total of 46 hours were accumulated during the first half of 1987 bringing the total operational hours to 202. The testing consisted of baseline Mod I BOM split-solid, Mod II type single solid, and "hot" piston rings. The hot rings were tested with split-solid rings in the lower groove and in both lower and upper grooves. In the former case, power was low indicating leakage. In the latter case, however, both power and efficiency increased substantially compared to the BOM baseline. The hot piston ring data were still being reviewed by NASA at the time of this report. Details of the single solid ring tests were discussed in Section II, Cold Engine System Development. Engine No. 10 is currently inactive.

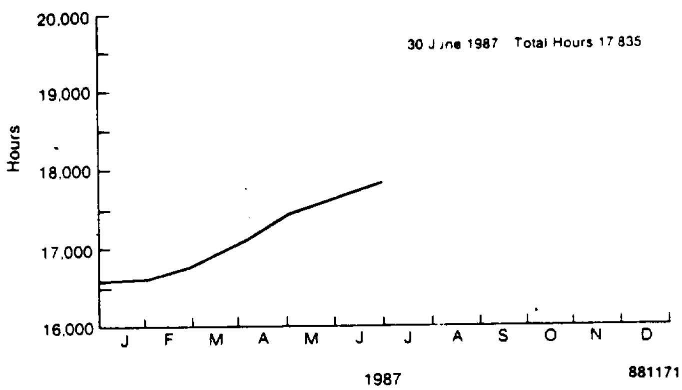
Upgraded Mod I Engine No. 11

Engine No. 11 is currently in storage at USAB. During this semiannual report period, a total of 115 hours were accumulated, which is also the total operational hours on the engine.

Upgrading of the engine from Mod I configuration (Mod I Engine No. 3) was completed during the first half of 1987. Initial tests were conducted using Mod I/Mod II heater heads (Mod II diameter tubes) and both power and efficiency were found to be low. The heads were subsequently replaced with new, upgraded Mod I heater heads, and the performance test repeated. Since performance was still below that obtained with Engine No. 9 (Figure 3-4), the latter was selected for use in the Air Force pickup truck.



a) Hours by Engine



b) Total Accumulated Hours

Fig. 3-1 Mod I Engine Test Hours

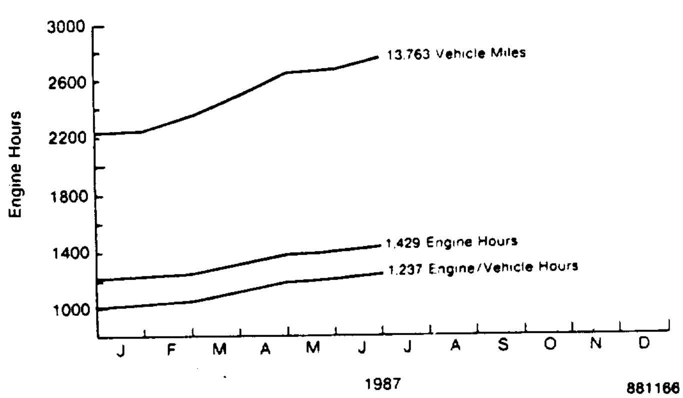


Fig. 3-2 Hours and Mileage for Upgraded Mod I Engine No. 8 Installed in the Spirit Vehicle

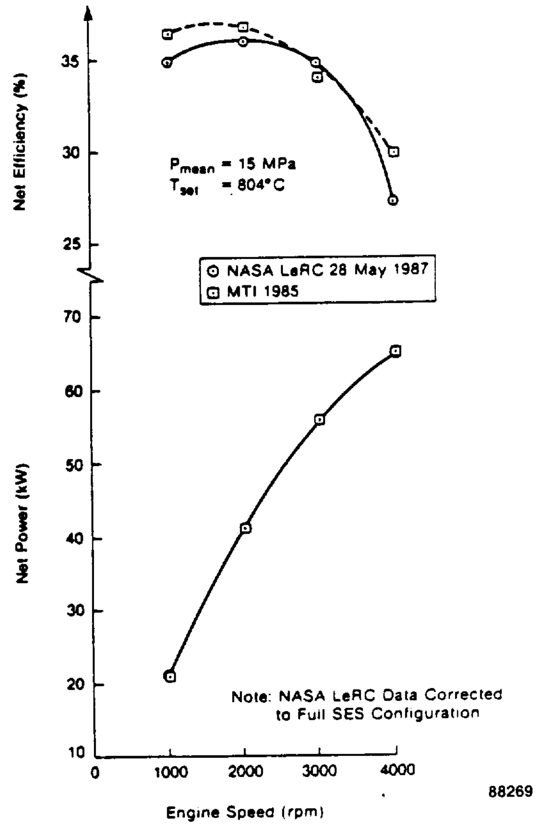


Fig. 3-3 Upgraded Mod I Engine No. 9 Performance

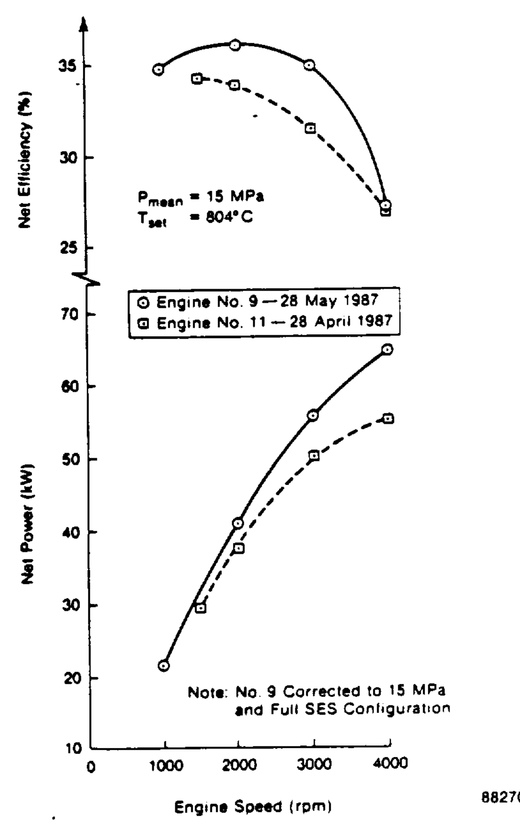


Fig. 3-4 Upgraded Mod I Engine Performance Comparison

IV. MOD II ENGINE DEVELOPMENT

Introduction

During this report period, the major design objectives were configuration No. 4 (no manifold) heater heads, a revised single solid type piston assembly, and support for engine testing.

The engine development program indicated a sharp increase in test hours, using the analog block engine to complete a BSE characterization as well as demonstrate the affects of regenerator porosity, working gas, and EHS parameters on engine performance. Configuration No. 4L heater heads were fabricated and tested, providing a marginal gain in power. The experience led to the design of a No. 4S configuration, which will have improved manufacturability and performance.

Analytical efforts were directed toward evaluating test data in order to determine future design and development paths and validate codes. The codes continue to be improved through the incorporation of test results. Several recorded updates were performed in order to predict where the current engine configuration stands relative to the final program mileage and acceleration goals.

Mod II Design

Configuration No. 4L Heater Heads

Design modifications were necessary to allow the fabrication and assembly onto the Mod II engine of the first set of configuration No. 4 heater heads. These heads have been designated 4L (L for long) because the average tube length was 90 mm longer than the design intent. The increase was caused by the limited development time available to determine tube routing and the complexity of bends required to assemble into the no-manifold housing, Figure 4-1.* Although the tube geometry is complex, the cast heater head housing is simple, Figure 4-2.

Initial assembly attempts of configuration No. 4L quadrants were unsuccessful because of the difficulty in achieving simultaneous location and alignment of the 24 tube ends at the floorplate location. The cramped vertical space between the top of the housing and the combustor floorplate, combined with the number of tube bends required, made assembly impractical. By reversing the tube couplings at the floorplate point and raising the floorplate 5 mm, assembly was possible.

Although the four configuration No. 4L quadrants were successfully assembled and brazed, the brazing fixture did not constrain the tubes properly, allowing the gap to widen at the top of the hairpin. The tubes and fins had to be modified to allow assembly onto the engine. The brazing fixture was redesigned to correct this flaw.

Configuration No. 4S Heater Heads

Configuration No. 4 heater heads were redesigned to correct the fabrication problems encountered with No. 4L and to reduce tube length. The redesign, designated 4S (S for short) was completed during this semiannual report period, Figure 4-3. The concept was demonstrated using solid copper tubes. By careful routing, it was possible to reduce the average tube length to 460 mm (minimum 450, maximum 500). This compares to the

*Figures are at end of this section, beginning on page 4-13.

approximate 540 mm of configuration No. 4L and 450 mm design intent. The advantage of 4S is reduced dead volume and pumping losses. The latter results from shorter tubes and fewer bends. At the end of this report period, the length of 4S tubes were increased another 38 mm in order to increase the length of rear-row finned tubes 19 mm, based on analytical projections that the benefits from increased heat transfer area more than offset the higher pumping losses.

Other design changes incorporated into the 4S design include a straight, parallel-to-rear row, front tube row and relocated tube coupling. The first change provides for uniform front row spacing and enhanced heat transfer. The second change replaces the two tube couplings at the bottom of the front and rear rows with a single coupling in the horizontal section between rows.

Single Solid Piston Rings

The Mod II engine has been operating with an older Mod I type split-solid piston assembly. The Mod II single solid type piston assembly has not been used because of the inability of that design to pass piston rod fatigue proof tests, as discussed in the "Materials and Process Development" section.

In order to reap the benefits of single solid piston rings (e.g., reduced friction and active dead volume during transients), a design was conceived that would allow the split-solid type pistons to be modified for use with single solid rings, Figure 4-4. The vent holes between the two sets of rings and the single hole in the piston rod are plugged. A hole is then drilled from the upper ring groove into the piston interior and a plastic pintle valve installed. The valve is contained by an O-ring and the single solid piston ring. During operation, the pintle valve prevents the gas inside the piston from participating in the working cycle but allows excess pressure to be vented during disassembly.

This hardware is being procured and will be tested in the Mod II engine.

Engineering Support

A number of Mod II design support activities were completed during this report period:

- Selection of cooler plating material
- Sealed CGR combustor (see "EHS Development")
- EGR combustor
- Reduced-friction water pump
- Post-shutdown coolant circulation system redesign
- Alternative dual-alternator mounting.
- Improved blower assembly (see "Control Systems/Auxiliaries Development").

Early experience with chrome-plated coolers had proved that this material was incompatible with the Rulon-LD piston rings. Based on earlier rig data, aluminum-oxide coating and nitrided steel both offer superior wear rates, Figure 4-5. The acceptability of these materials has been demonstrated in the Mod II engine and motoring rig, respectively.

The reduced-friction water pump redesign consists of undercutting the outer diameter of the outer gerator to reduce liquid shear losses. This concept will be evaluated in a test rig during the next report period. After-cooling is now provided by a small high-speed dc motor and speed reduction gear driving the pump after the engine has stopped. The previous pancake motor design proved to be inadequate.

The two-alternator mounting consists of a conventional alternator on the same shaft as the permanent magnet alternator, the first for battery charging and the second for blower power. Alternatively, a two-conventional alternator mounting scheme is also being considered.

Other support activities were provided for

- Phase I NASA TU van
- Phase II NASA TU pickup truck
- Celebrity
- Mod II motoring rig.

Mod II Engine Test Program

During the first half of 1987, 316 hours of testing were accomplished on engine No. 1 using an analog steel block in BSE configuration. As of the end of this semiannual report period, a total of 538 hours had been achieved (Figure 4-6) in the test cell.

Major development tests completed during this time period were:

- BSE performance characterization
- Emissions characterization
- Alternate porosity regenerators (65, 68.2, and 70%)
- Working gas evaluation (H_2, He, and N_2)
- Lambda/atomizing airflow optimization
- Noise evaluation
- Configuration No. 4L heater heads.*

On the hardware side, the cold engine and drive system (CEDS) problems with the coolers, crosshead liners, and crossheads, which had previously limited Mod II testing, were resolved. Total CEDS hours at the end of the report period without significant wear or failure in Mod II Engine No. 1 were:

- Ion-nitrided coolers: 316 hr (+12 on motoring unit)
- Drive system: 525 hr
- Crosshead liners: 353 hr
- Main seals and piston rings: 316 hr (except cylinder No. 3 lower rings).

During the next report period, the engine will be reconfigured with cast block, single solid piston rings, reduced cold space dead volume, and built-up into SES configuration. The latter incorporates the Mod II MPC, blower, blower drive system, and battery charge system. A second engine will also be built for installation in the test cell when the first is installed in the Celebrity vehicle.

BSE Performance Characterization

The BSE characterization test was completed using the analog block, ion-nitrided coolers, configuration No. 1 (two manifold) heater heads, Mod II atomizing air compressor, Mod I blower, and Mod I hydrogen compressor. Results are illustrated in Figures 4-7 through 4-10. The maximum power and efficiency were 53.9 kW and 38.0%, respectively, less than the analytical projections for this configuration (Figures 4-11 and 4-12).

The rear row set temperature used during the test is illustrated in Figure 4-13. The decrease at low fuel flows is necessary to keep front row temperatures within design limits. This is a consequence of the unique configuration No. 1 geometry, where the front row is connected to the regenerator. The limitation is removed with configuration No. 4, which has the front row connected to the expansion space. The rear row temperature variation was in excess of the design goal of 100°C for some of the points (Figure 4-14). This will be reduced by modifications to the combustor.

The ability of the engine to sustain performance is illustrated in Table 4-1,** which confirms no degradation after 150 hours with a single build.

Emissions Characterization

The Mod II engine, as previously described, was characterized for NO_x, CO, HC, and soot emissions. The results were discussed under "EHS Development."

*In progress.
**Table 4-1 is on following page.

TABLE 4-1
MOD II ENGINE PERFORMANCE AFTER
150 HR OF OPERATION
(820°C SET TEMPERATURE)

Total Hours	Rejected Heat to Coolant (kW)	Heat Added as Fuel (kW)	Heat to Engine (kW)	Net Power (kW)	Net Efficiency (%)
Maximum Power (15 MPa, 4000 rpm)					
258	97.8	185.4	161.2	53.2	28.7
410	99.7	186.6	161.2	51.7	27.7
414	99.4	186.5	169.6	53.0	28.4
418	90.9	187.9	162.6	54.1	28.7
Maximum Efficiency (15 MPa, 1500 rpm)					
258	36.5	75.7	67.5	28.8	37.8
410	37.2	78.1	68.2	28.3	36.2
414	37.3	78.3	68.4	28.4	36.3
418	36.6	77.7	68.1	28.9	37.3

Regenerator Porosity/Working Gas

These tests were conducted at 820 and 720°C set temperatures, respectively, in the configuration previously described. The results are discussed under "Mod II Analysis." As a part of the working gas test, helium control and hydrogen short circuiting were also evaluated.

Lambda/Atomizing Airflow Optimization

Tests were conducted to determine the minimum levels of these variables that could be used while still meeting program goals for soot ($\leq$10), gaseous emissions, and heater head temperature variation. The engine configuration was unchanged. Heater head set temperature was 820°C. The results and conclusions of the test were previously discussed under "EHS Development."

Noise Evaluation

The engine configuration remained unchanged. Helium was used as the working gas and operation was at a 720°C set temperature. A sound intensity meter was used for the measurements that were made on each side and the top of the engine. The imaginary cube was 4 × 4 × 4 ft. A total of 20 measurements were made for each data point. The test points, results, and comparison to internal combustion engines are discussed in "Mod II Analysis."

Configuration No. 4L Heater Heads

The change to configuration No. 4L heater heads was accomplished after the modifications discussed in the preceding section, Mod II Design. The no-manifold configuration No. 4 design was expected to reduce dead volume and, hence, improve both power and efficiency. These advantages were somewhat compromised by the long tube 4L hardware that had to be used initially. The short 4S design, which will be tested in the next report period, achieves close to the design intent for tube length and, therefore, dead volume, as described under "Mod II Design."

Once the heads were assembled onto the engine, the transition piece was modified to raise the preheater and combustor in order to accommodate the increased floorplate height. The remaining parts of the engine were the same as the preceding tests.

The testing demonstrated a slight increase in power (55.2 kW), compared to configuration No. 1, and several functional problems. The latter were primarily the result of the modifications made to fit the heater head onto the engine. After sealing potential leak paths on both combustion and working gas sides, it was determined that front row and combustion gas after tube temperatures were higher than expected. The leak paths were the combustor to heater head seal and quadrant deck plate gaps on the combustion side and a partition wall to cylinder housing gap on the working gas side.

The projected causes of the high front row temperature were increased flame temperature, displaced combustion, or poor combustor mixing. Increased flame temperature could result if heater head combustion side pressure drop had increased and had thereby reduced the amount of CGR. Measurements of EHS pressure drop, however, showed no increase (Figure 4-15). NO_x emissions were also unchanged, indicating the same percent CGR as with configuration No. 1. Measurements of CO, HC, and soot did not reveal a displaced burning zone. The final possibility, combustor maldistribution, will be confirmed during the next report period by changing the combustor configuration.

The cause of high combustion gas after tube temperatures was inadequate heat transfer area. Configuration No. 4S heater heads have been designed to correct this deficiency.

Further details of the performance with configuration No. 4L heater heads are contained in "Mod II Analysis."

Mod II Hardware

During this report period, the basic reliability of the CEDS was demonstrated using analog block engine No. 1.

Early experience with chrome-plated coolers had demonstrated rapid wear when used with Rulon LD piston rings. These were replaced with ion-nitrided 329 stainless steel and demonstrated acceptable wear. Limited motoring rig testing of aluminum-oxide-coated coolers have also indicated acceptable wear.

Installing type-A, cast-iron crosshead liners and opening the clearance between the liner and crosshead to 0.05-0.06 mm has been successful in eliminating wear and galling without affecting main seal life.

Cast V-blocks have been successfully fabricated and are available for Mod II engine testing. The first two of these contained leaks in the cold-connecting duct area. An epoxy impregnation technique was developed that allows these pin-hole leaks to be sealed as demonstrated by fatigue tests. Subsequent blocks have no leaks but are impregnated to ensure all pores are sealed. The Koyo bearings and crankshafts to be used with the cast blocks are also on hand.

The fabrication of configuration No. 4L heater heads was described in "Mod II Design." The exercise was successful in pointing out design and fabrication difficulties, which will be corrected with configuration No. 4S; three sets of which will be manufactured during the next report period. Combustor fabrication and durability improvements have been discussed under "EHS Development."

Based on fatigue test results showing the unacceptability of the single solid type ring assembly, modifications have been made to some of the split-solid types to allow the use of single solid piston rings. Pending a successful engine test, the remainder will be converted.

Mod II Analysis

Efforts during this report period were devoted to the effects of regenerator porosity, working gas, combustion air blower efficiency, and configuration No. 4L heater heads on performance. An evaluation of the impact of a PCV failure on vehicle operation was completed and the Mod II scorecard updated. Noise measurements of the Mod II BSE were also compared to other engines.

Regenerator Porosity

An engine test was conducted with three sets of different porosity regenerators: 70%, 68.2% (nominal design), and 65%. The purpose was to confirm that the design porosity was the optimum, engine performance was fairly insensitive to variations within this range, and the validity of analytical predictions. The tests were conducted at 820°C set temperature with configuration No. 1 (two manifold) heater heads.

The results confirmed that the optimum porosity is 68.2% and that performance is only slightly affected by porosity changes, Figures 4-16 through 4-19. Power at 3000 rpm and higher speeds is reduced with 65 and 70% porosity regenerators, with the former being more pronounced. Efficiency at speeds below 2000 rpm is slightly increased for the 65% porosity regenerators. The heater head set temperature during the 65% test, however, was about 5°C higher than for the other two. Adjustment for this difference reduces the low-speed efficiency gain and increases the high-speed power reduction with the 65% porosity regenerators.

The agreement between measured and predicted power and efficiency was found to be reasonable, Figures 4-20 through 4-23.

Working Gas

Tests were conducted with hydrogen, helium, and nitrogen working gases in order to validate the Stirling-cycle code over a range of gas properties and determine performance decrements associated with helium and nitrogen, as opposed to hydrogen. Test conditions were 720°C rear row set temperature and 50 and 70°C coolant inlet temperatures.

Predicted versus measured data for various cycle parameters indicated good agreement. Using hydrogen as an example:

Parameter	Predicted vs Measured Correlation (%)	
Engine net power	+10	
Engine net efficiency	<1	
Cycle power	+√5,	Fig. 4-24*
Heat to cycle	+√8,	Fig. 4-25
Heat rejected to coolant	+√10,	Fig. 4-26
Working gas temperature	-√7,	Fig. 4-27
Compression space gas temperature	<1,	Fig. 4-28
Compression space amplitude/mean pressure	+√7,	Fig. 4-29
Compression space pressure phase angle	+√3,	Fig. 4-30
Expansion space amplitude/mean pressure	√7,	Fig. 4-31
Expansion space pressure phase angle	√3,	Fig. 4-32

A comparison of performance with different working gases revealed that power decreases in the order of hydrogen, helium, and nitrogen (Figure 4-33), as expected. Since the Mod II is designed for hydrogen, power increases with the speed and achieves a maximum at the rated speed of 4000 rpm. Substitution of helium or nitrogen lowers the speed at which maximum power is achieved due to increased pumping losses and reduced heat transfer. A comparison of net efficiencies (Figures 4-34 through 4-36) reveals a similar trend. Since the Mod II is optimized for part power operation, the substitution of helium results in only a slight reduction in maximum efficiency. That is because at low speed, the difference in pumping losses is not significant.

Combustion Air Blower

An analysis was completed on the impact of blower performance on vehicle mileage and acceleration. The actual Mod II blower aerodynamic performance was found to be different from predicted at higher head rises, Figure 4-37. The impact on vehicle performance, however, is estimated to be negligible, Table 4-2.**

Configuration No. 4L Heater Heads

During the test and evaluation of configuration No. 4L heater heads in the Mod II

*For clarity, figures show only measured data.
**Table 4-2 is on following page.

TABLE 4-2
CELEBRITY PERFORMANCE WITH
DESIGN AND CURRENT BLOWER

	Design	Current
Acceleration 0-60 mph, sec	14.55	14.80
Urban CVS mileage, mpg	27.41	27.37
Highway CVS mileage, mpg	51.88	51.80
Combined CVS mileage, mpg	34.79	34.76

engine, predictions were continuously compared to the data and updated as necessary.

Prior to engine evaluation, the heater head quadrants were flow tested with air to determine working gas side pressure drop and flow distribution (Figure 4-38) Reynolds numbers corresponding to engine operation were used. Flow variation was determined to be ±6% compared to ±16% for configuration No. 1.

Flow tests using pressurized nitrogen were also conducted on the configuration No. 4 regenerators, which feature larger mesh size screen and reduced porosity compared to those used with configuration No. 1 heater heads. The pressure loss was found to be close to that predicted, Figure 4-39.

Measurements of the cold side dead volume of the analog steel block used for all Mod II engine tests to date revealed an extra 23 cc/cycle:

	Volume (cc) Modeled	Volume (cc) Measured
Cold ring	38.71	52.45
Connecting duct	31.57	29.55
Cold space clearance	5.10	16.33
Total	75.38	98.33
Difference	22.95	

This additional volume enables predicted pressure amplitudes to match those measured.

The combined impact of increased heater head pressure loss and dead volume on engine power is illustrated in Figure 4-40. This loss will be recouped by reducing dead volume with future cast blocks and use of lower pressure loss configuration No. 4S heater heads previously described. In the latter case, shorter tubes with fewer bends will reduce pressure drop.

Analytical efforts were also devoted to determining the reasons for higher-than-expected front row and combustion gas after tube temperatures, as discussed under "Mod II Engine Test Program." At the end of the report period, it had been concluded that the higher front row temperatures may be due to combustion maldistribution and that the high after tube temperatures are the result of inadequate heat transfer area. Additional tests are planned to address the former and the design of configuration No. 4S has been altered to increase the length of the finned rear row to address the latter.

Impact of a Power Control Valve Failure

One of the concerns about using a Stirling engine in a vehicle with mean pressure control and short circuiting is what impact a PCV failure would have on vehicle control. Specifically, if loss of power or signal to the PCV occurs the valve will be driven to the short-circuit/dump positions to dissipate engine power and prevent uncontrolled acceleration. Could the negative torque generated by this dissipation cause the drive wheels to lock and/or loss of vehicle control?

In order to answer this question, a Mod II engine map with full short circuiting was generated using the HFAST code, Figure 4-41. Using this map with the known Celebrity vehicle transmission* and drive train characteristics, it was concluded that on a dry road, tire slippage is only possible at speeds less than 8 mph. If the road is wet, this can occur only at speeds less than 12 mph. In either case, the low speed would prevent loss of vehicle control. The maximum deceleration rate, again at low speed, would be about 11.9 mph/sec if the PCV fails, Figure 4-42. This compares to a maximum vehicle deceleration rate of 18.7 mph/sec without the slippage. Thus, a PCV failure would only cause a deceleration rate about 2/3 of that of which the vehicle is capable without loss of control.

It was concluded that a PCV failure would not cause loss of vehicle control or injury to the occupants. A test was performed on the upgraded Mod I Spirit vehicle on the chassis dynamometer confirming these predictions.

Mod II Scorecard Update

Periodically, the performance predictions of the Mod II powered Celebrity are updated to reflect the latest engine configuration and test results and compared to the original projections made for the Mod II SES Design Review in August 1985. A total of three updates were made during this semiannual report period.

The final update reflects the following differences from those assumed during the SES Design Review:

1. Revised crosshead loss model based on boundary layer lubrication with partial contact

2. Higher water pump losses as determined from test data

3. Revised EHS efficiency, Figure 4-43, reflecting increased atomizing airflow to control soot emissions and reduced CGR, Figure 4-44, and EHS pressure drop as determined from test data.

4. Reduced blower performance as discussed under "Control System/Auxiliaries Development."

5. Reduced alternator performance

6. Increased electrical load (606 versus 345 W)

7. Revised H_2 compressor round pumping losses based on test data

8. Configuration No. 4L heater heads with 90-mm long tubes (538 versus 448 mm) and increased bend losses, Figures 4-45 and 4-46.

The net result of these changes is illustrated in Table 4-3** for the engine maximum efficiency point where SES power has remained nearly constant but efficiency is reduced 0.9% point to 35.6%. A total of four engine operating points were considered in the analysis, Table 4-4. The update indicates a reduction in full load net power and efficiency as well as reduced net efficiency at all points. A detailed breakdown of the impact of some of the changes made since the SES design review on Celebrity vehicle performance is given in Table 4-5. A comparison of the first row to the last indicates estimated CVS combined cycle mileage decreasing from 40.9 to 34.8 mpg and 0-60 mph acceleration time increasing from 12.4 to 14.6 sec since the SES design review.

*The study assumed a manual transmission. An automatic transmission with torque converter would not be as great a concern due to the soft coupling between engine and drive train.

**Table 4-3 is on page 4-9, Table 4-4 is on page 4-10, and Table 4-5 is on page 4-11.

TABLE 4-3
PREDICTED MOD II SES MAXIMUM
EFFICIENCY POINT PERFORMANCE

	Revised Prediction	SES Design Review
Pmean (MPa)	15.0	15.0
N (rpm)	1250	1200
EHS Data		
λ (-)	1.25	1.25
m_{aa} (g/sec)	1.00	0.36
CGR (%)	39.0	80.0
Thtr-f (°C)	776	-
Thtr-r (°C)	820	820
CWS Data		
m_{cw} (kg/sec)	1.25	1.25
Tcw-in (°C)	41.8	41.8
Tcw-out (°C)	50.0	50.0
Cycle Losses (kW)		
Pumping	0.90	0.80
Conduction	1.81	1.81
Reheat	3.79	-
Leakage	1.80	-
Drive Friction (kW)		
Piston Rings	1.21	1.20
Main Seals	0.61	0.55
Bearings	0.25	0.25
Crosshead	0.95	0.09
Oil Pump/Seals	0.22	0.21
Auxiliaries (kW)		
Alternator	0.90	0.51
Blower	0.52	0.48
Water Pump	0.27	0.25
H_2 Compressor	0.30	0.21
Cycle Power (kW)	31.44	30.00
BSE Power (kW)	27.63	27.24
SES Power (kW)	26.20	26.25
Eta, b (%)	90.7	91.1
Eta, eff (%)	35.6	37.5
m_f (g/sec)	1.72	1.63

The program goal of a 30% improvement in combined cycle fuel economy relative to an internal combustion engine requires a mileage of 40.3 mpg (1.3 × 31.0). The 0-60 mph acceleration goal of 15.0 sec is still met. The 34.8 mpg prediction reflects the current (updated) version of the Mod II engine. The final engine configuration will incorporate the following improvements to ensure at least a 30% improvement in fuel economy:

1. Configuration No. 4S heater heads featuring reduced tube length and bend losses and enhanced heat transfer (increased rear row finned length and reduced front row tube spacing)

2. Single solid piston rings that reduce drive system losses and reduce dead volume during transients

3. Reduced water pump losses through redesign

4. Reduced electrical load via a reduction in solenoid valve power requirements and improved blower drive system

5. Reoptimized regenerator.

During the next report period these improvements will be incorporated into hardware and performance evaluated in the Mod II engine.

Mod II BSE Noise Analysis

Noise measurements of the Mod II engine in BSE configuration were made for comparison to conventional gasoline and diesel engines. Five load points were measured, as indicated in Table 4-6.* A sample result for the vehicle design point is shown in Figure 4-47, where the view is from the top of the engine with the four sides folded out. The frequency distribution for this same point is

*Table 4-6 is on page 4-12.

TABLE 4-4
PREDICTED MOD II SES PERFORMANCE

	SES Design Review	Current Heater No. 4 without Bend Losses	Current Heater No. 4 with Bend Losses
Full Load Point (P = 15 MPa, n = 4000 rpm)			
Indicated Power (kW)	78.6	72.6	68.6
Friction (kW)	9.9	9.8	9.7
Auxiliaries (kW)	6.4	9.0	8.9
Net Power (kW)	62.3	53.7	50.0
EHS Efficiency (%)	88.9	89.6	89.6
Net Efficiency (%)	28.2	24.6	23.3
Part Load Point (P = 12 kW, n = 2000 rpm)			
Indicated Power (kW)	15.7	16.4	16.4
Friction (kW)	2.0	2.0	2.0
Auxiliaries (kW)	1.6	2.4	2.4
Net Power (kW)	12.1	12.0	12.0
EHS Efficiency (%)	90.4	90.1	89.1
Net Efficiency (%)	33.2	30.5	30.2
Maximum Efficiency Point (P = 15 MPa, n = 1250 rpm)			
Indicated Power (kW)	30.4	31.4	31.3
Friction (kW)	2.5	3.2	3.2
Auxiliaries (kW)	1.3	2.0	2.0
Net Power (kW)	26.6	26.2	26.1
EHS Efficiency (%)	91.0	90.7	90.7
Net Efficiency (%)	38.5	35.6	35.5
Low Load Point (P = 5 MPa, n = 1000 rpm)			
Indicated Power (kW)	9.1	8.9	8.8
Friction (kW)	0.9	1.0	1.0
Auxiliaries (kW)	1.0	1.7	1.7
Net Power (kW)	7.2	6.2	6.1
EHS Efficiency (%)	88.8	85.8	85.8
Net Efficiency (%)	32.3	26.7	26.6

TABLE 4-5
CELEBRITY VEHICLE ESTIMATED PERFORMANCE

	Map No.	Mileage (mpg) Urban with CSP	Highway	Combined	Idle Conditions m_f (g/sec)	N (rpm)	Accel. 0-60 mph (sec)
Heater No. 3; SES Review Loss Models; 1 Fan*	133-01	32.9	58.2	40.9	0.159	400	12.4
Heater No. 4L; Loss Models for Current Drive and Auxiliary Components; No Bend Losses; 1 Fan*	100-00	29.5	53.9	37.0	0.198	600	13.6
Design Heater No. 4; SES Review Loss Models; No Bend Losses; 1 Fan*	101-00	32.7	57.0	40.5	--	400	12.4
Design Heater No. 4; SES Review Loss Models, Except Revised X-Head Loss Model; No Bend Losses, 1 Fan*	101-01	32.0	55.9	39.7	0.139	400	12.9
Same as 101-00 with Bend Losses; 1 Fan*	101-02	32.7	56.9	40.4	0.124	400	12.8
Same as 101-01 with Bend Losses; 1 Fan*	101-03	32.0	55.7	39.6	0.139	400	13.4
Same as 100-00 with Bend Losses; 2 Fans**	100-01	27.4	51.9	34.8	0.311	600	14.6

*1 fan with η drive = 1.0 below 20 mph; no fan above 20 mph.
**2 fans with η drive = 0.6 at all speeds.

illustrated in Figure 4-48. The variation in sound power level as a function of speed indicated a range from 78 dBa at idle to 108 dBa at maximum power, Figure 4-49.

TABLE 4-6
MOD II BSE NOISE MEASUREMENT
POINTS AND RESULTS

Engine Condition:	rpm	P_m MPa	Sound Power dBa
Idle	500	3	78.1
Generator Set Full Load	1800	12	95.5
Vehicle Design Point	2000	5	94.5
Heat Pump Full Load	2200	12	97.7
Maximum Power	4000	15	108.0

Comparison to a Deere and Company diesel generator set indicated lower sound power levels for the Mod II, Table 4-7. A similar comparison to Ford gasoline vehicle engines revealed slightly higher Mod II levels, Table 4-8.

TABLE 4-7
MOD II/DEERE DIESEL
SOUND POWER COMPARISON

Deere Model: 4239D
Rated: 56 kW at 2500 rpm
Air Inlet, Exhaust, and Radiator Cooling Fan Outside of Noise-Measurement Volume

	Sound Power, dBa re 1 pW	
Condition	Mod II BSE	Deere 4239D
Slow Idle	78.1 (500 rpm)	97.0 (800 rpm)
Rated Power	108.0 (2000 rpm)	111.0 (2500 rpm)
	94.5 (2000 rpm)	

TABLE 4-8
MOD II/FORD GASOLINE
SOUND POWER COMPARISON

(Tested in Vehicle with Hood Up in Reverberant Room; B&K Type 3360 Sound Intensity Analyzing System)

	Sound Power, dBa RE 1 pw			
	No Load		Road Load at 55 mph 3000 rpm	
Engine Size	1000 rpm	4000 rpm	in Neutral	Loaded
1.6I4	76.9-77.5	99.3-100.5	98.7	98.6
1.9I4	76.9-77.5	99.3-100.5		
2.0I4	76.0	96.3		
2.3I4	78.6	102.3		
2.8V6	77.3	99.5		
3.0V6	74.9-80.4	96.1-102.9		
5.0V8	81.4	106.1		
Mod II	84.0 (Interpolated)	108.0		

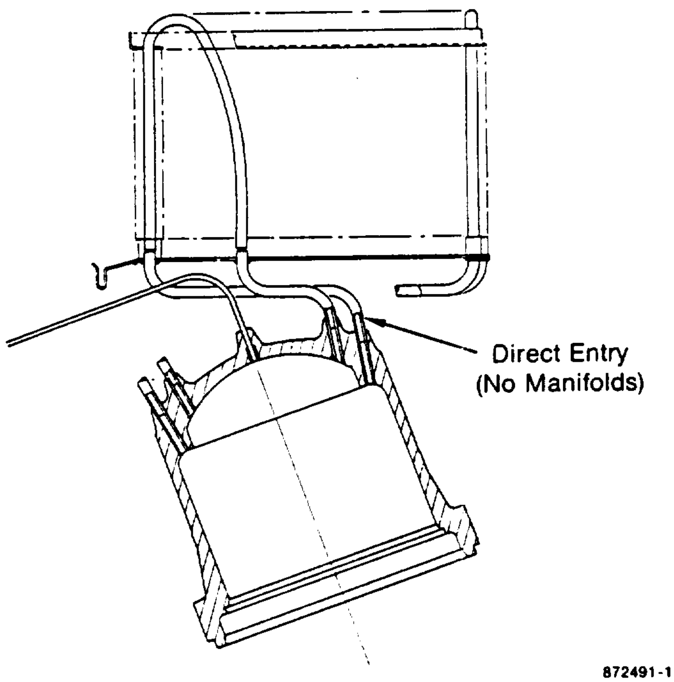


Fig. 4-1 Configuration 4L Heater Head

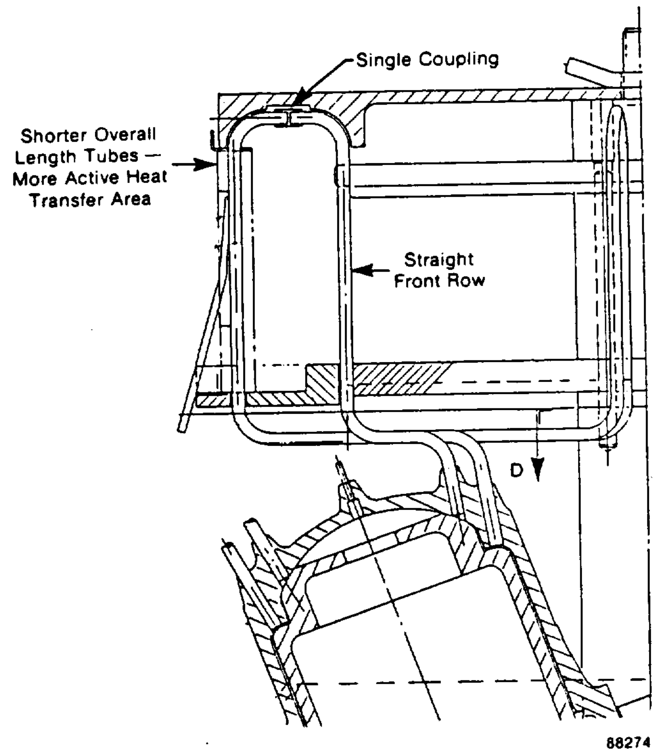


Fig. 4-3 Configuration No. 4S Heater Head

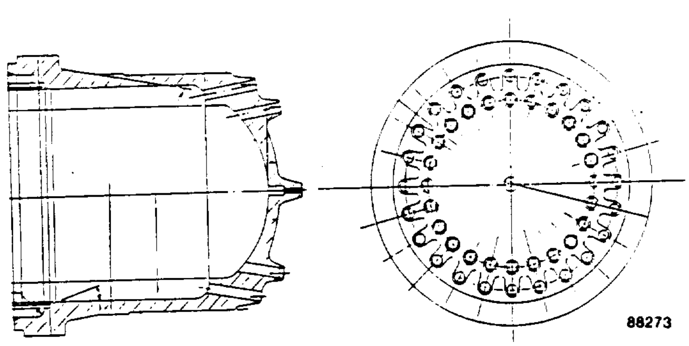


Fig. 4-2 Mod II Configuration No. 4 Heater Head Housing

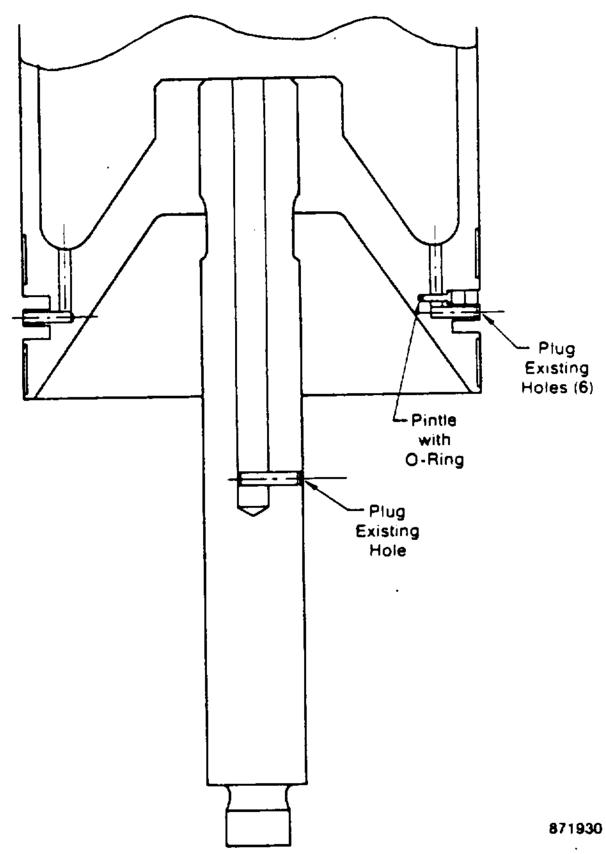


Fig. 4-4 Mod II Piston Rod Modification to Use Single Solid Piston Rings

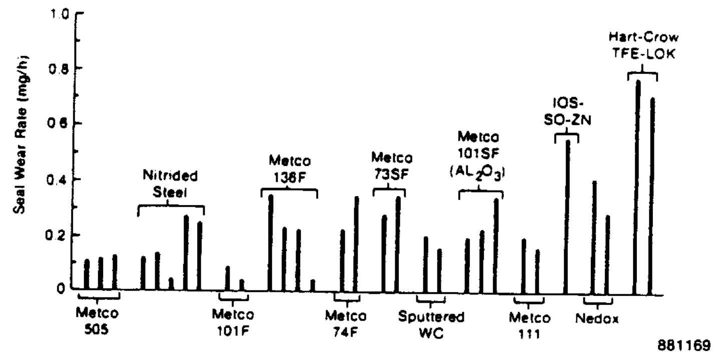


Fig. 4-5 Seal Wear Rate for Different Materials with Rulon L-D

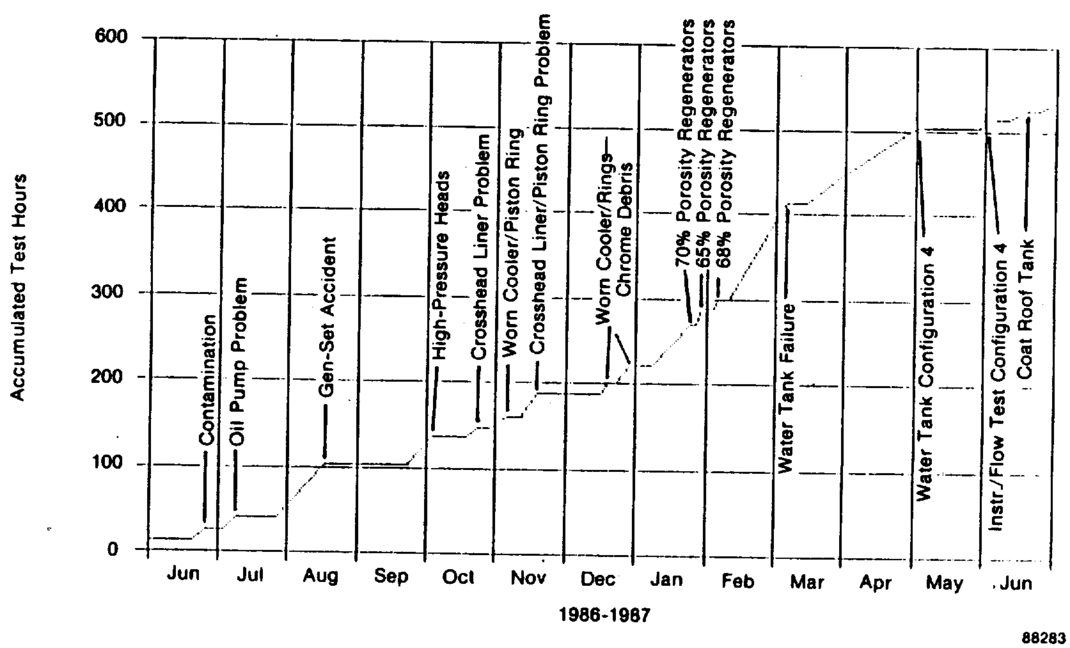


Fig. 4-6 Mod II Engine No. 1 Test Hours

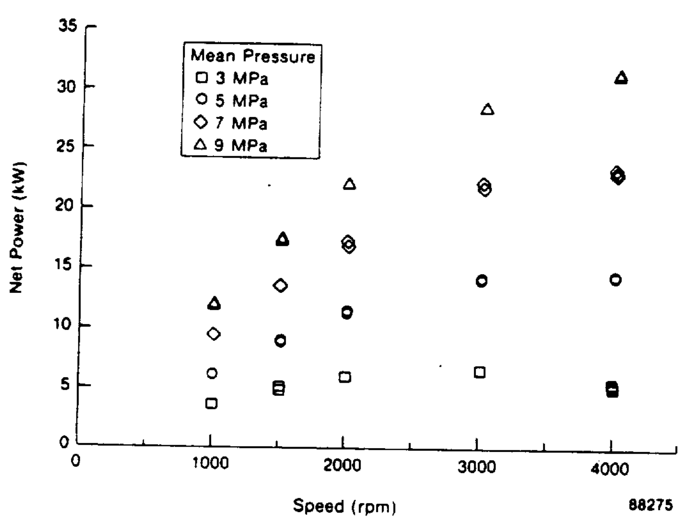


Fig. 4-7 Mod II BSE Net Power at 3 to 9 MPa

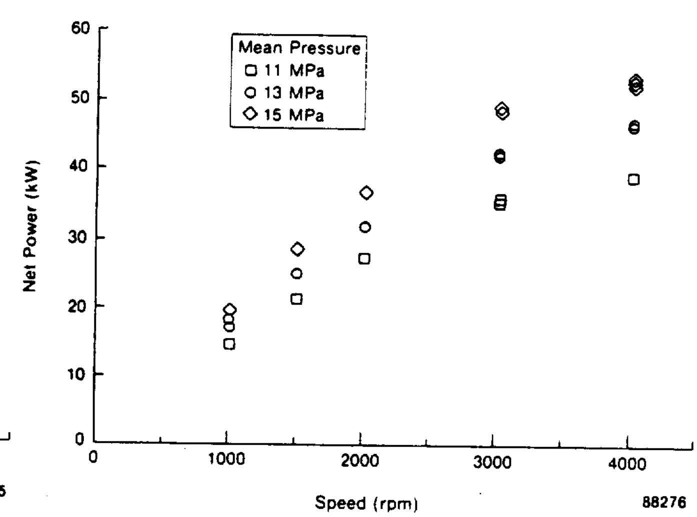


Fig. 4-8 Mod II BSE Net Power at 11 to 15 MPa

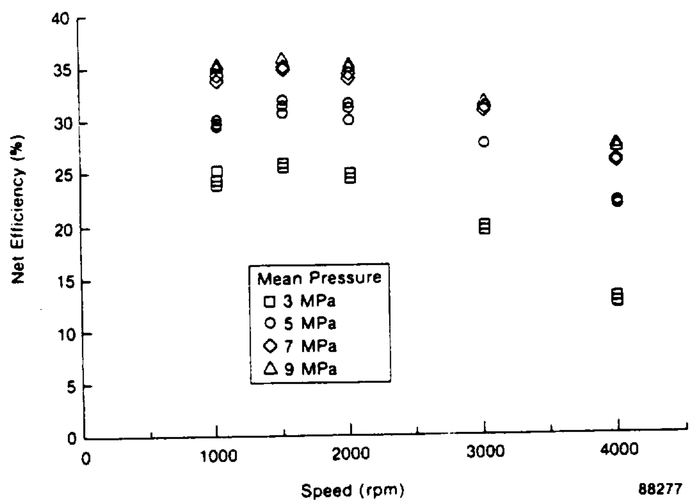


Fig. 4-9 Mod II BSE Net Efficiency at 3 to 9 MPa

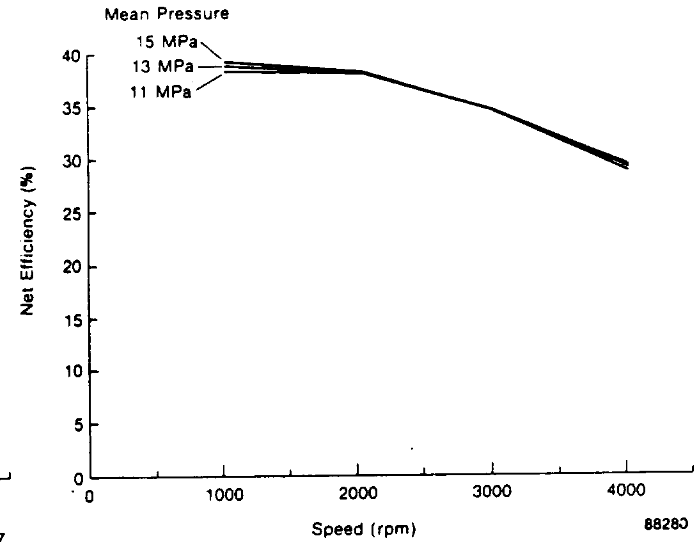


Fig. 4-12 Predicted Mod II BSE Net Efficiency

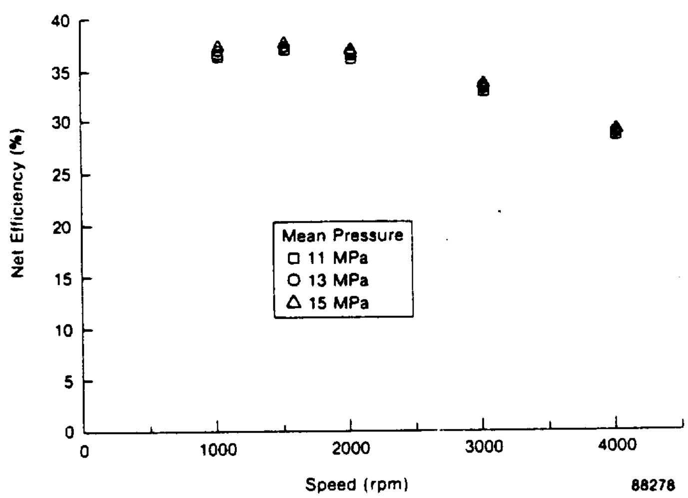


Fig. 4-10 Mod II BSE Net Efficiency at 11 to 15 MPa

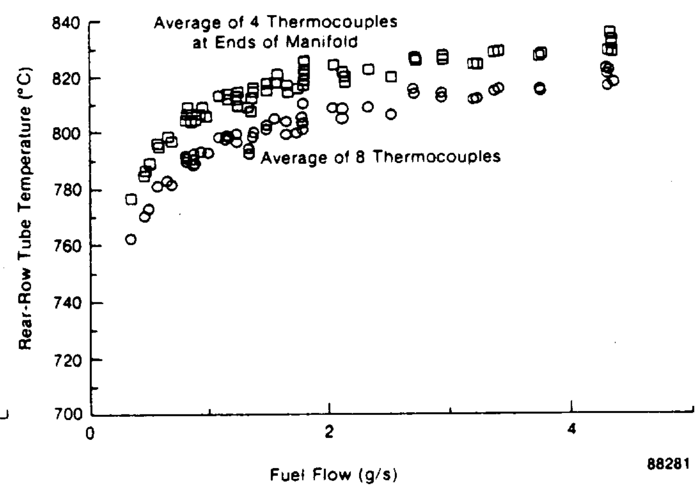


Fig. 4-13 Mod II BSE Characterization Test Set Temperature

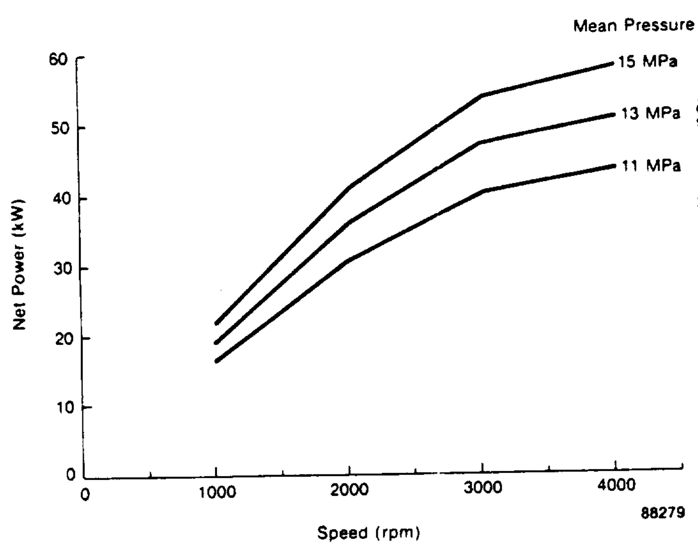


Fig. 4-11 Predicted Mod II BSE Net Power

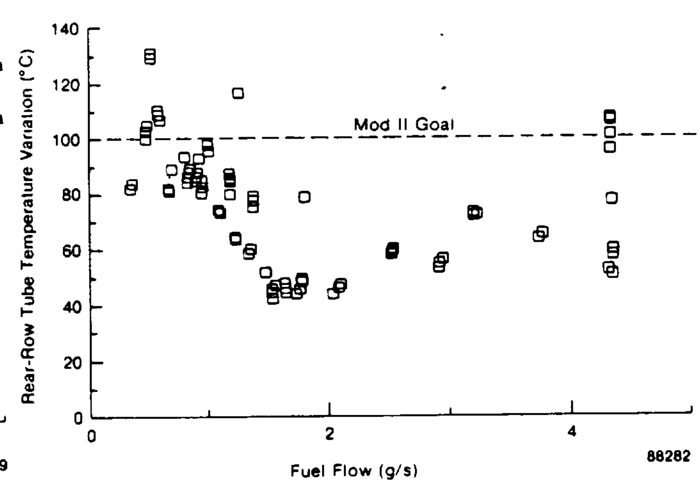


Fig. 4-14 Mod II BSE Characterization Test Tube Temperature Variation

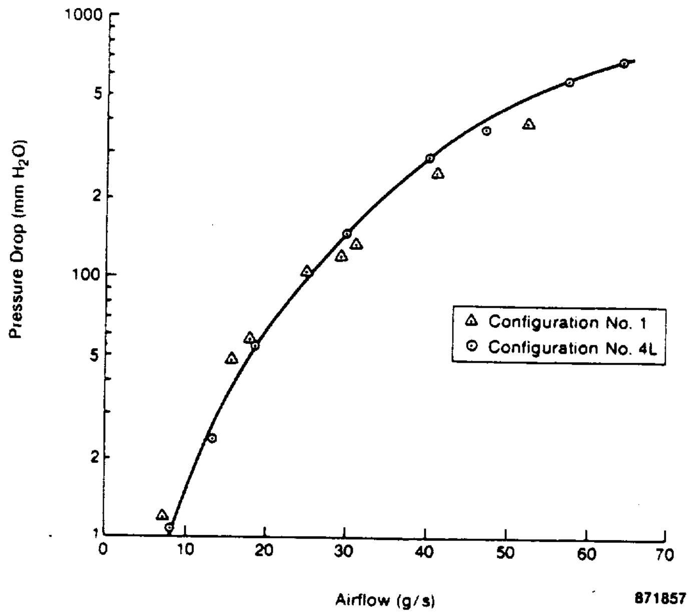


Fig. 4-15 Mod II Combustor and Heater Head Pressure Drop

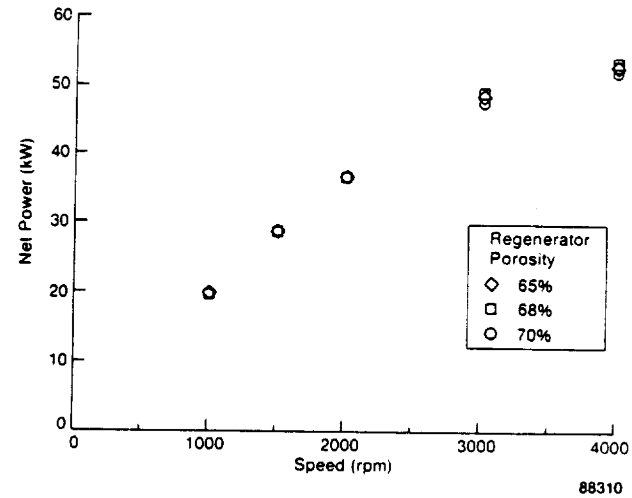


Fig. 4-18 Effect of Regenerator Porosity on Mod II BSE Net Power at 15 MPa and 820°C

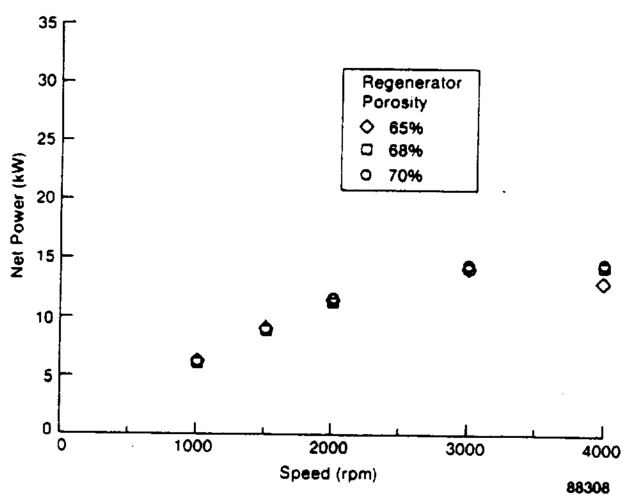


Fig. 4-16 Effect of Regenerator Porosity on Mod II BSE Net Power at 5 MPa and 820°C

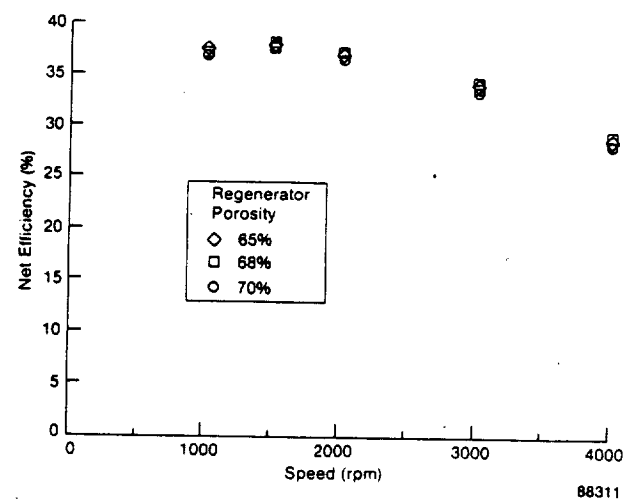


Fig. 4-19 Effect of Regenerator Porosity on Mod II BSE Net Efficiency at 15 MPa and 820°C

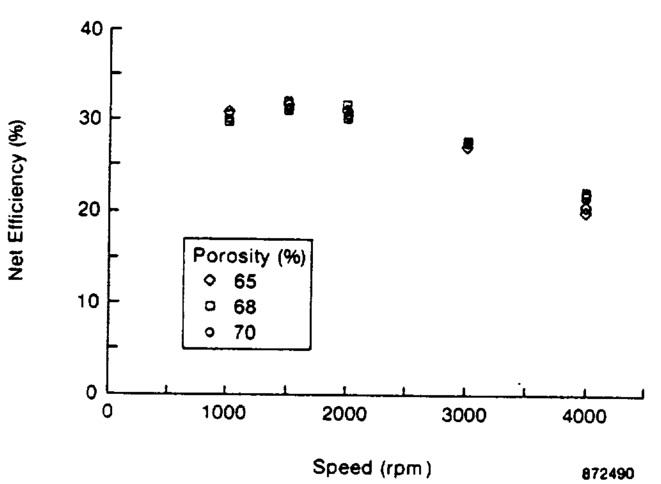


Fig. 4-17 Effect of Regenerator Porosity on Mod II BSE Net Efficiency at 5 MPa and 820°C

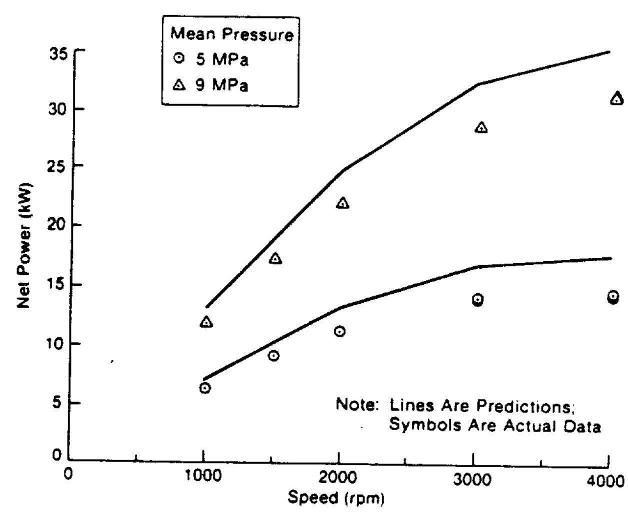


Fig. 4-20 Mod II BSE Net Power with 70% Porosity Regenerators

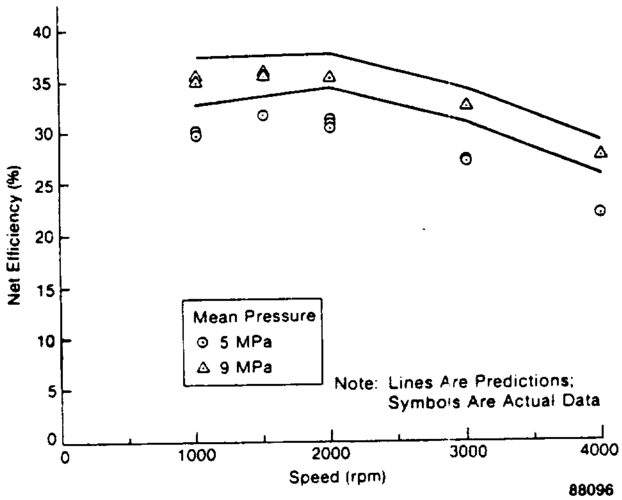


Fig. 4-21 **Mod II BSE Net Efficiency with 70% Porosity Regenerators**

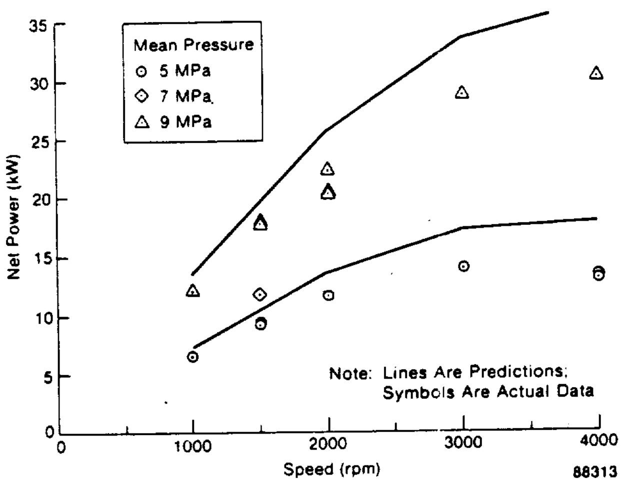


Fig. 4-22 Mod II BSE Net Power with 65% Porosity Regenerators

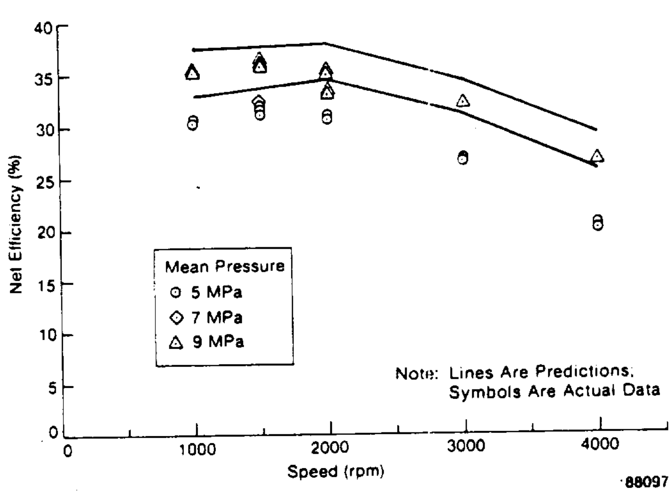


Fig. 4-23 Mod II BSE Net Efficiency with 65% Porosity Regenerators

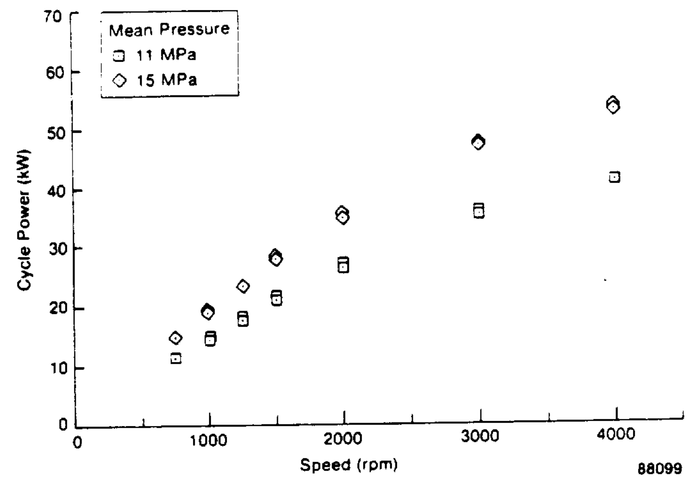


Fig. 4-24 Mod II Cycle Power with Hydrogen

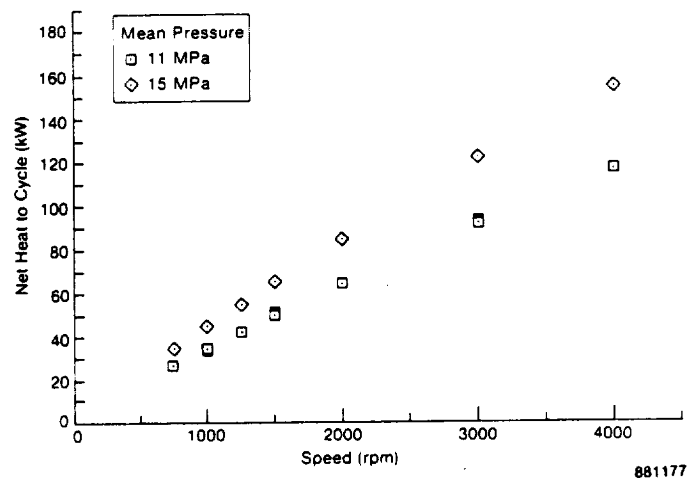


Fig. 4-25 Mod II Net Heat to Cycle with Hydrogen

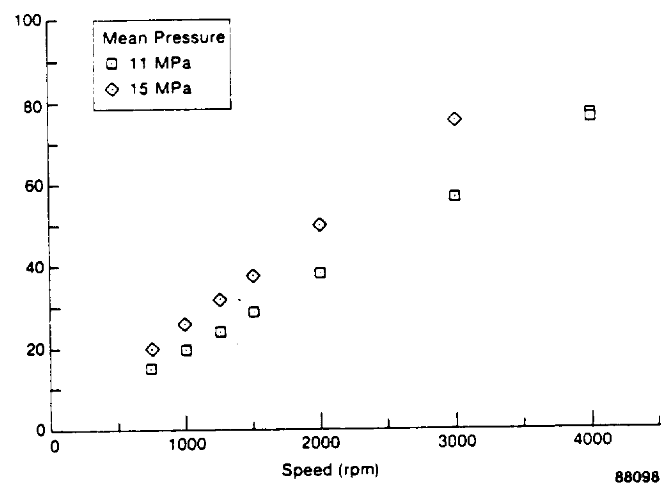


Fig. 4-26 Mod II Heat Rejected to Cycle with Hydrogen

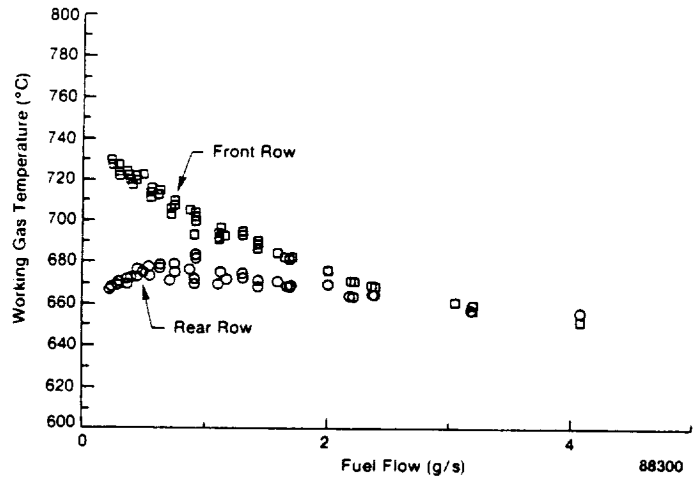


Fig. 4-27 Mod II Hydrogen Working Gas Temperature

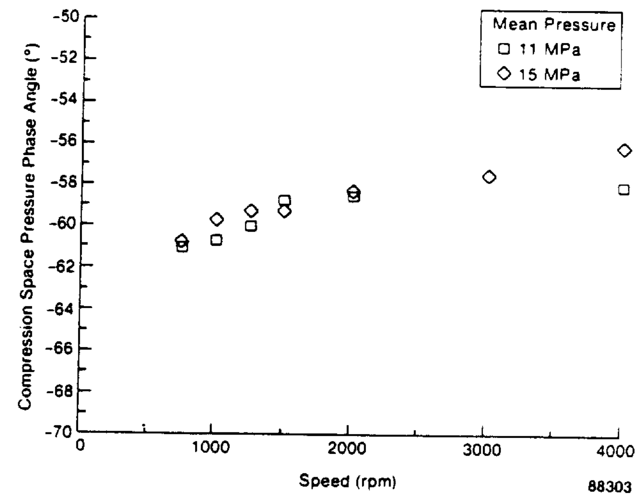


Fig. 4-30 Mod II Compression Space Pressure Phase Angle with Hydrogen

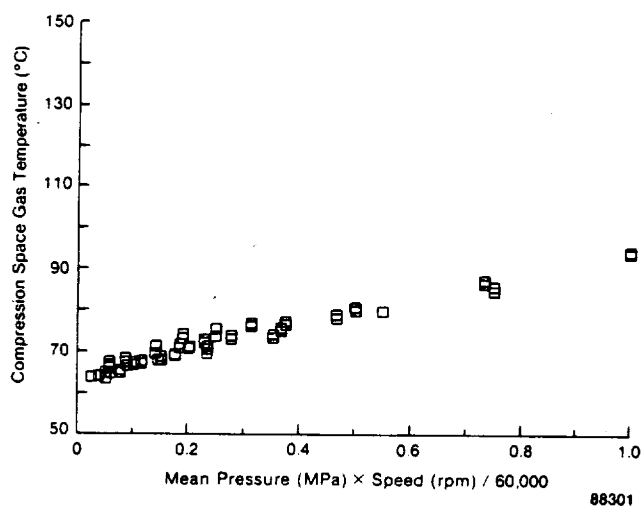


Fig. 4-28 Mod II Compression Space Hydrogen Temperature

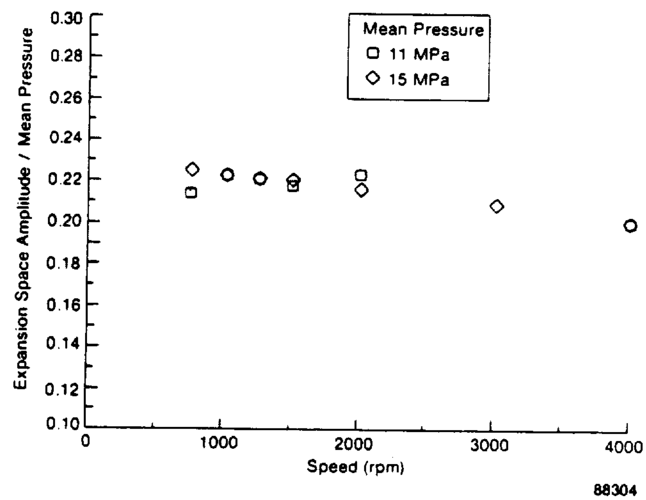


Fig. 4-31 Mod II Expansion Space Pressure Ratio with Hydrogen

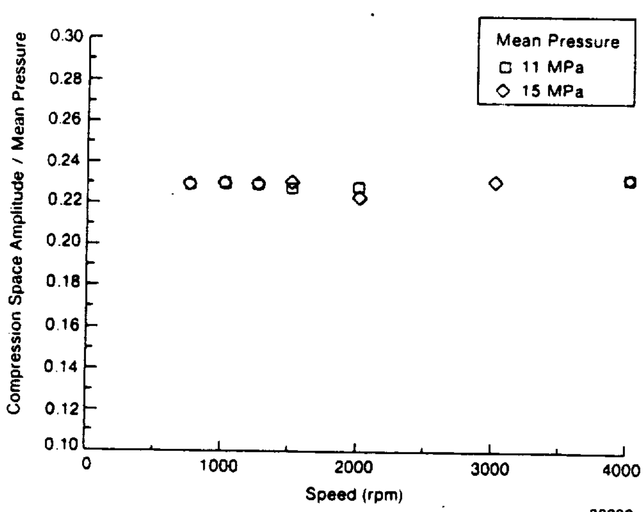


Fig. 4-29 Mod II Compression Space Pressure Ratio with Hydrogen

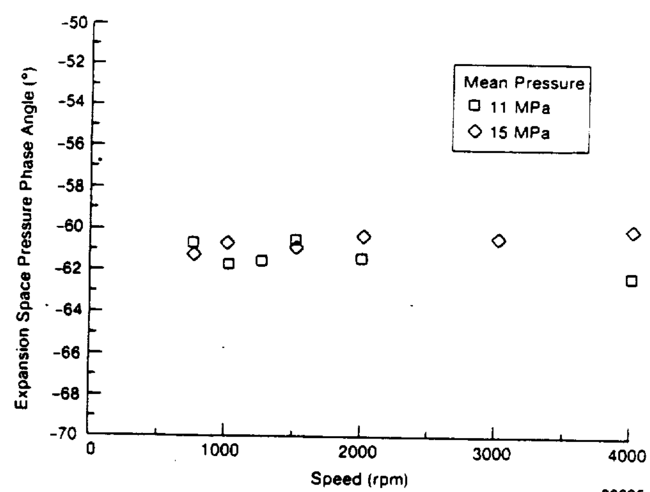


Fig. 4-32 Mod II Expansion Space Pressure Phase Angle with Hydrogen

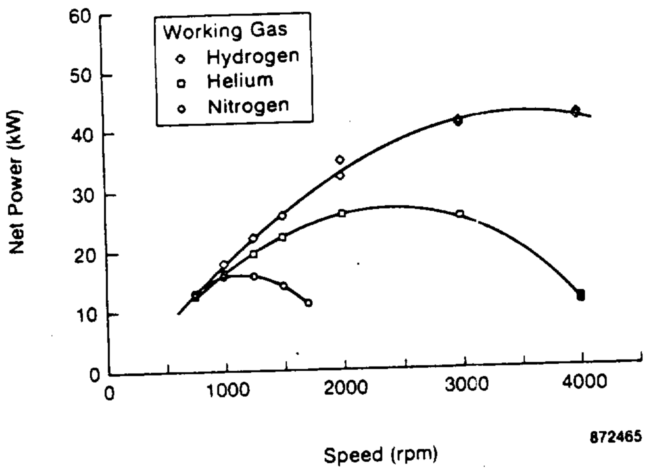


Fig. 4-33 Mod II New Power with Various Working Gases at 15 MPa

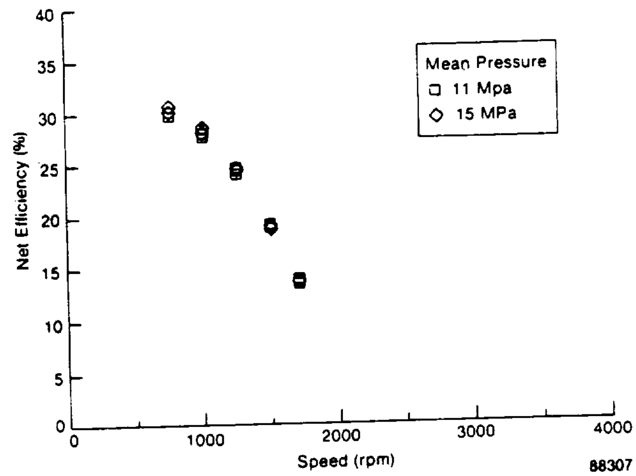


Fig. 4-36 Mod II BSE Net Efficiency with Nitrogen at 720°C

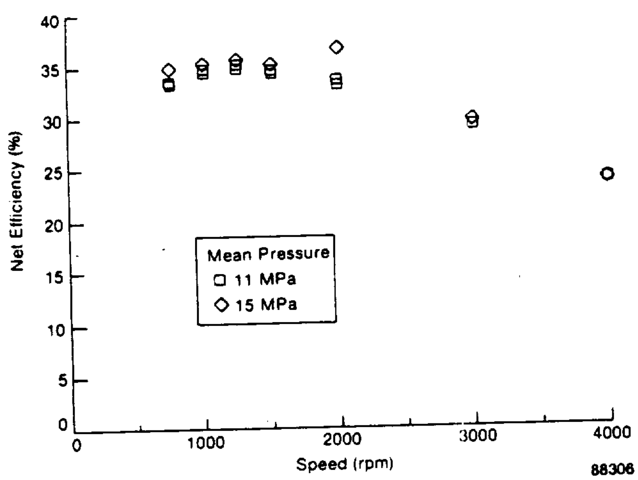


Fig. 4-34 Mod II BSE Net Efficiency with Hydrogen at 720°C

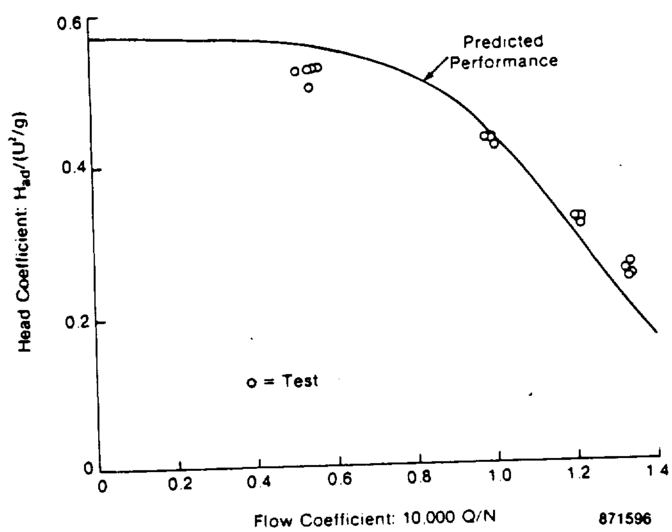


Fig. 4-37 Predicted and Test Performance of Mod II Combustion Air Blower

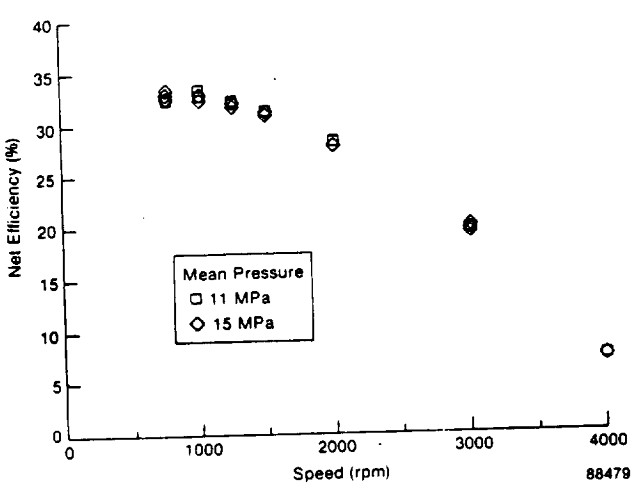


Fig. 4-35 Mod II BSE Net Efficiency with Helium at 720°C

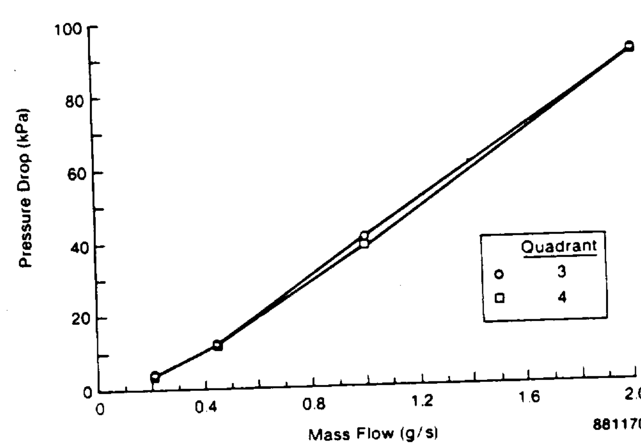


Fig.4-38 Mod II Configuration No. 4L Heater Head Pressure Drop

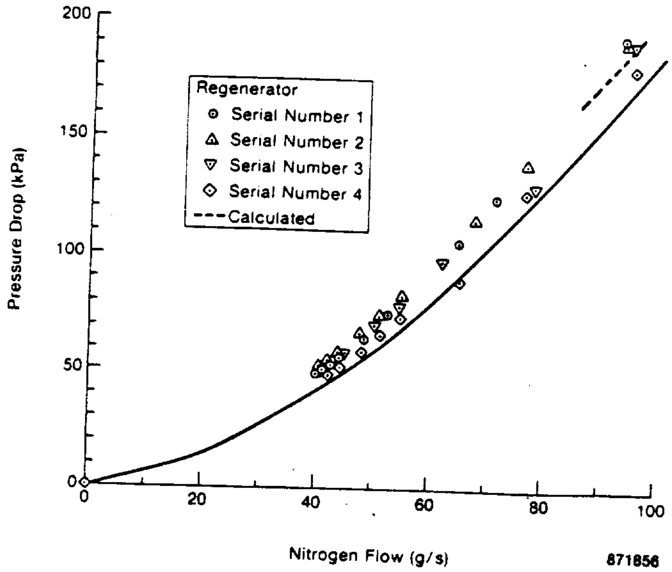


Fig. 4-39 Flow Testing of Mod II Heater Head No. 4 Regenerators

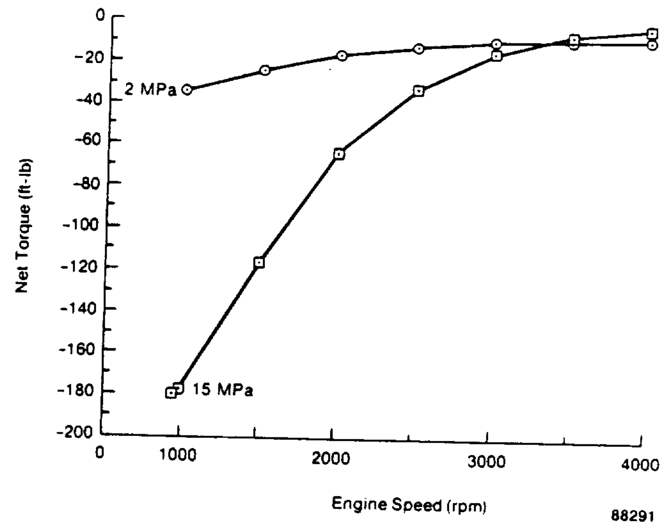


Fig. 4-41 Predicted Mod II SES Net Torque with Full Short Circuiting

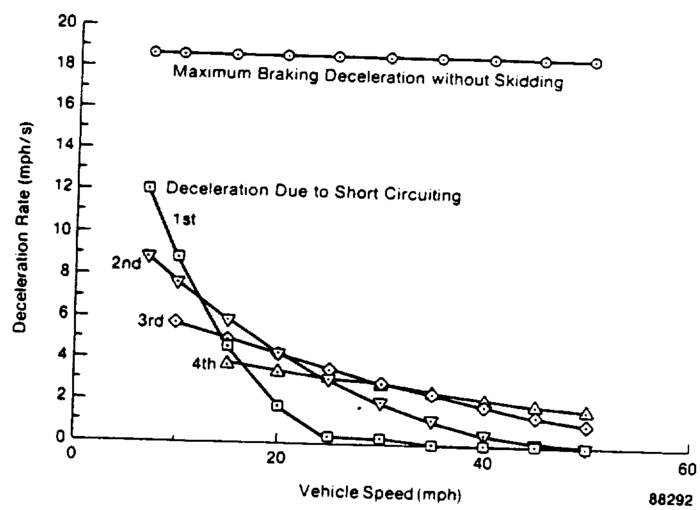


Fig. 4-42 Effect of Short Circuiting on Vehicle Dynamics

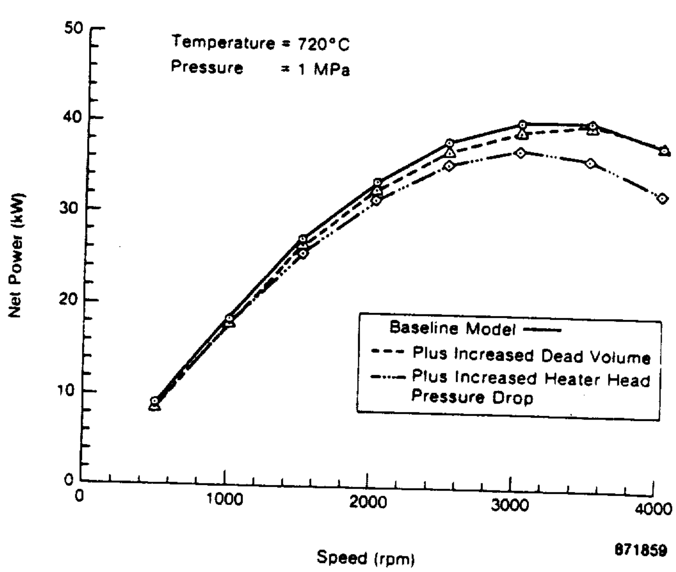


Fig. 4-40 Effect of Increased Heater Head Dead Volume and Pressure Drop on Mod II Heater Head No. 4 Net Power

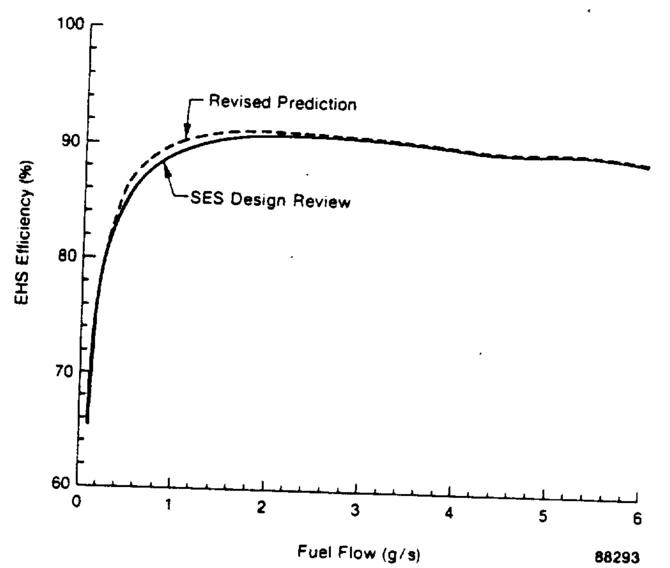


Fig. 4-43 Mod II EHS Thermal Efficiency

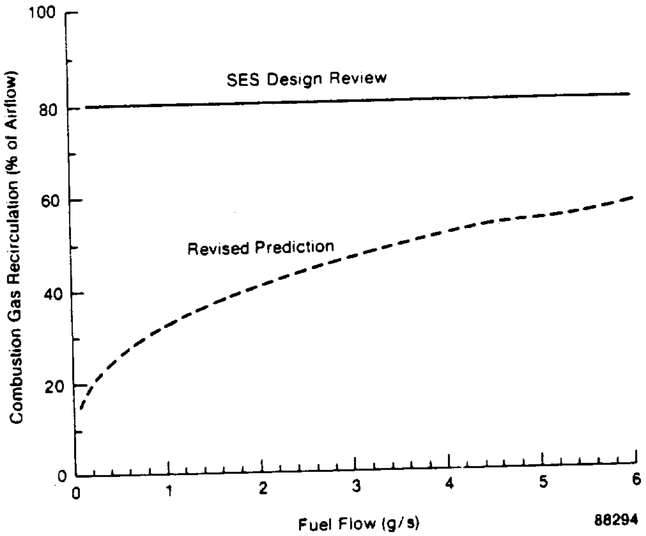


Fig. 4-44 Mod II CGR

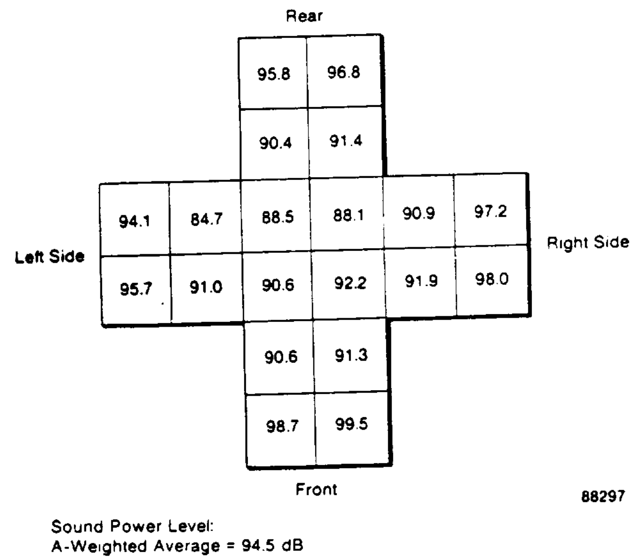


Fig. 4-47 Mod II BSE Sound Intensity at Vehicle Design Point

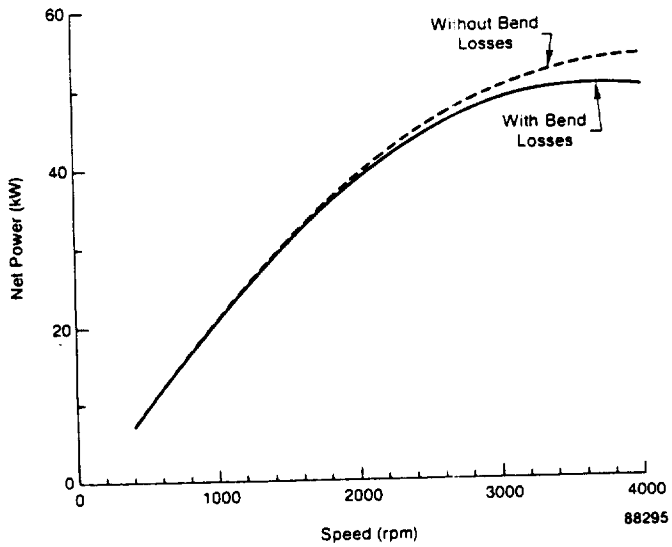


Fig. 4-45 Predicted Mod II SES Net Power at 15 MPa with Configuration No. 4L

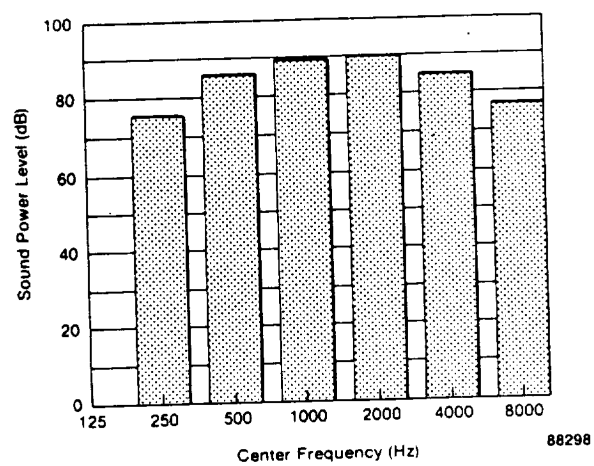


Fig. 4-48 Mod II BSE Sound Intensity Frequency Distribution at Vehicle Design Point

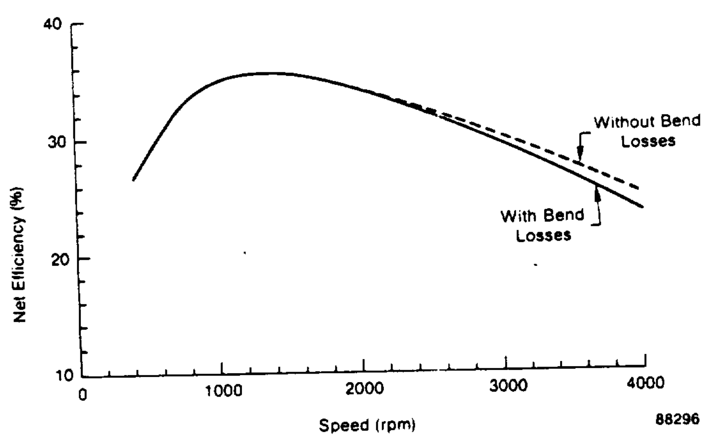


Fig. 4-46 Predicted Mod II SES Net Efficiency at 15 MPa with Configuration No. 4L

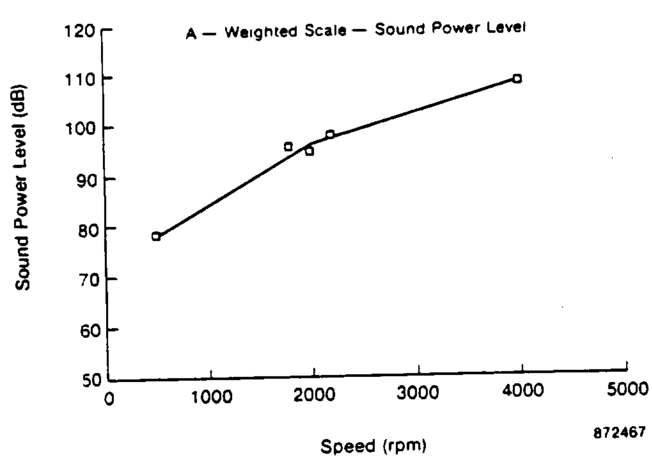


Fig. 4-49 Mod II BSE Sound Levels

V. PREPRODUCTION STIRLING ENGINE SYSTEM COST STUDY

The purpose of this task is to determine the manufacturing cost of a complete SES engine. The costing is being performed by Deere and Company and utilizes a value analysis/value engineered (VA/VE) Mod II engine manufactured in quantities of 15,000/yr. The study is divided into five phases:

- Phase I - CEDS manufactured parts
- Phase II - EHS, HES, controls, and auxiliaries manufactured parts
- Phase III - Remaining manufactured parts, including routings and machine tools for primary operations
- Phase IV - Purchased parts
- Phase V - Assembly, test, and trim operations required to produce a finished engine ready for shipment. This includes tooling and facilities.

As of the end of this report period, Phases I and II have been completed and work initiated on Phase III. Summary cost data from the first two phases are given in Tables 5-1 and 5-2* (1986 dollars). An overhead rate of 600% of direct labor was used. The direct labor rate assumed was $13/hr. The VA/VE study resulted in a 32% savings for Phase I and a 49% savings for Phase II resulting in total cost per VA/VE Mod II engine of $2546, Table 5-3. An example of the cost reduction obtained with a VA/VE piston rod assembly is given in Figure 5-1.**

TABLE 5-3
PHASE I AND II COST PER
VA/VE MOD II ENGINE

Total Costs for Proposed Components:	
Phase I:	$17,274,100
Phase II:	20,915,100
Total to Date:	$38,189,200
Cost Per Engine:	$ 2,545.95

Phases I and II have evaluated 76% of the manufactured parts of the engine. Phase III will be completed during the next report period.

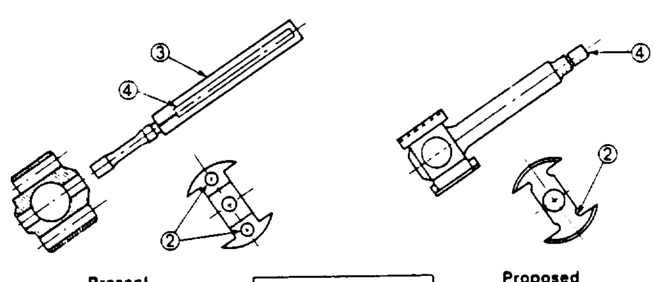
*Tables 5-1 and 5-2 are on the following page.
**Figure 5-1 is on page 5-3.

TABLE 5-1
PHASE I DEERE VA/VE STUDY

Description	Estimated Annual Cost at 15,000 Units/yr		Savings	
	Present Design	Proposed Design	Annual	%
Piston Rod and Crosshead	2,050,800	754,800	1,296,000	63.2
Piston and Radiation Shield	1,902,600	1,648,200	254,400	13.4
Cooler Tubes	3,024,000	1,800,000	1,224,000	40.5
Cooler Shell	450,000	152,400	297,600	66.1
Cooler Body	2,116,200	1,902,000	214,200	10.1
Final Assembly, Cooler	1,449,000	1,235,400	213,600	14.7
Main Seal Housing Assembly	1,828,800	898,800	930,000	50.9
Crankshaft Assembly	2,073,450	1,187,550	885,900	42.7
Water Pump	2,592,450	1,934,250	658,200	25.4
Oil Pump Proposal Summary	--	--	--	--
Oil Pump Assembly	69,300	23,100	46,200	66.7
Housing, Oil Pump	327,600	236,250	91,350	27.9
Cover and Screen, Oil Pump	36,150	11,250	24,900	68.9
Gear and Shaft, Oil Pump	143,100	22,500	120,600	84.3
Cover Plate, Oil Pump	230,400	10,800	219,600	95.3
Heater Head Attachment	790,650	45,450	745,200	94.3
Engine Block Casting	2,939,400	2,691,900	247,500	8.4
Wrist Pin	271,100	37,450	233,650	86.2
Connecting Rod	1,905,000	1,678,200	226,800	11.9
Ring Clamp	282,600	157,500	125,100	44.3
Clamping Plate, Check Valve	660,300	620,700	39,600	6.0
Insulating Cover	95,400	86,400	9,000	9.4
Bellows	160,350	139,200	21,150	13.2
TOTAL	25,398,650	17,274,100	8,124,550	32.0
			($542 Per Engine)	

TABLE 5-2
PHASE II VA/VE STUDY

Description	Estimated Annual Cost at 15,000 Units/yr		Savings	
	Present Design	Proposed Design	Annual	Percent
Heater Head Housing	748,050	279,450	468,600	62.64
Heater Tube Assembly	7,927,200	4,432,800	3,494,400	44.08
Front Cover	432,750	324,450	108,300	25.03
Oil Sump	371,400	115,800	255,600	68.82
Combustor	3,041,850	1,290,600	1,751,250	57.57
Preheater	10,609,800	2,677,950	7,931,850	74.76
Blower	951,750	712,350	239,400	25.15
Power Control Valve	6,642,000	5,445,900	1,196,100	18.01
Flamestone	395,400	282,750	112,650	28.49
Engine Block	3,503,700	2,883,750	619,950	17.69
Fuel Nozzle	746,100	261,900	484,200	64.90
H_2 Compressor	5,637,450	2,207,400	3,430,050	60.84
TOTAL	41,007,450	20,915,100	20,092,350	49.00



Total Cost	
Present	$39.18
Proposed	$12.58

(1) Combined two simple parts into one forging
(2) Eliminated two drilled holes with broached feature
(3) Replaced nitrided surface with hard chrome plating
(4) Eliminated axial vent hole; replaced with upper vent
(5) Eliminated TIG weld, rod-to-base; Part 0019

Fig. 5-1 Value Engineering Proposal — Piston Rod and Crankshaft Assembly

VI. TECHNICAL ASSISTANCE

NASA Technology Utilization Program

The NASA technology utilization (TU) program is designed to provide assessment of the ASE technology by a user party and to obtain participation in the evaluation by a major engine manufacturer. The U.S. Air Force and the postal service are the user parties; the manufacturer is Deere and Company. The Stirling engine is of interest to the Air Force and post office for reasons of fuel economy, multifuel capability, and potential for reduced maintenance. The demonstration will be conducted in three phases; the final phase intending to show readiness of the Mod II ASE engine in this application (Figure 6-1).* The first two phases are single vehicle evaluations and the third phase is a multivehicle fleet evaluation. Currently, Phases I and II are both active.

During this report period, the evaluation of the Phase I van was completed by the Air Force. The Phase II vehicle was selected to be a Dodge D-150 pickup truck. Conversion of that truck to Stirling power was begun. The decision to use a U.S. postal service long-lived vehicle (USPS LLV) for Phase III was made during August 1987.

During the next report period, a further evaluation of the Phase I van will be completed by Deere and Company. The conversion of the pickup truck will be completed and evaluation of the second vehicle begun by the Air Force. The study of how to install the Mod II into the USPS LLV will be also completed.

Phase I - Air Force Van

The objective of Phase I is to provide initial assessment of Stirling engine capability while in actual service use. The Phase I vehicle (Figure 6-2) is an Air Force multistop vehicle, used for personnel and equipment transportation on the flight line. This 6300-lb vehicle was originally powered by a 145-hp diesel engine. Its replacement with a 75-hp existing Stirling engine resulted in reduced acceleration capability. This was judged acceptable since the vehicle's maximum speed is limited to base speed limits, which rarely exceeds 35 mph. The vehicle was stationed at Langley Air Force Base to provide moderate environmental conditions. Evaluation of the vehicle started in the later half of 1986 and was completed during this report period. The initial operational goals were to achieve 1000 hours of operation on the flight line, using unleaded gasoline for the first 500 hours and JP-4 for the second 500 hours of operation. This was subsequently modified to include the use of diesel fuel.

The original goals were surpassed in all cases, as were the modified goals:**

	Modified Goals (hr)	Actual (hr)
Unleaded Gasoline	400	527
JP-4	400	536
Diesel	200	153
Total	1000	1216

*Figures are at the end of this section, beginning on page 6-4.
**Diesel goal was not attained due to funding constraints.

Upon completion of the U.S. Air Force evaluation at the end of this report period, the van was shipped to Deere and Company in Moline, Illinois, for evaluation in over-the-road interplant mail delivery service.

A summary of the cumulative operational time during Phase I is shown in Figure 6-3. The period of time with very little accumulation of operating hours was due to difficulties encountered with the engine control system. Upon resolution of the control problems, accumulation of operating hours proceeded at a high rate with relatively few problems encountered. The changeover from unleaded gasoline to JP-4 was uneventful and required only a checkout and verification period prior to return to service, since the engine air/fuel control had been initially set up to accommodate either fuel. A two-week period was required to configure the vehicle for diesel fuel in order to install a gasoline start-up system, Figure 6-4. The need for that system arose because the diesel requirement had not been identified in the initial engine build stages. With additional development, gasoline start-up would not be needed. After conversion, operation on diesel fuel proceeded uneventfully. Figure 6-5 presents a summary of the weekly and cumulative availability rates. The definition of availability is:

$$\frac{\text{In-Service Hours for 1 Week}}{168}$$

The period of time where control problems were experienced had a detrimental effect on availability rate. In the time period following correction of the control problems, the availability rate was approximately 84%. A formal assessment report of the multistop vehicle is currently being prepared by the Air Force and will be released independently of the ASE program.

Phase II - Air Force Truck

The objective of this phase is to provide user assessment of Stirling capabilities in over-the-road operation in a variety of environmental conditions. The evaluation will be conducted at Elgin Air Force Base, Florida (hot and humid), Randolph Air Force Base, Texas (hot and dry), and Offutt Air Force Base, Nebraska (high altitude, cold, and dry). A Dodge D-150 pickup truck was selected as the vehicle for this phase since its weight was better suited to the existing upgraded Mod I Stirling engine power output. The D-150 has a 3760-lb curb weight with a 95-hp internal combustion base engine. The upgraded Mod I Stirling replacement is 80 hp. In this report period, the engine for the vehicle was characterized and readied for installation. The vehicle was baselined and conversion to Stirling power was started.

The upgraded Mod I engine first selected for the D-150 was characterized and found to be a substandard performer. The second engine, characterized at the NASA-LeRC test cell, demonstrated acceptable performance and duplicated performance levels achieved with the engine in tests conducted several years earlier. The results of these tests were previously discussed in "Mod I Engine Test Program."

Baseline information was achieved for the D-150 pickup truck. The vehicle was weighed, accelerations were performed, and an over-the-road fuel economy check was performed. Using the results obtained on the Stirling engine during the NASA-LeRC testing, predictions for vehicle accelerations were generated and compared to baseline information (Table 6-1).* The acceleration rates are anticipated to be somewhat slower due to the lower power rating of the Stirling engine.

*Table 6-1 is on following page.

TABLE 6-1
DODGE D-150 PICKUP TRUCK ASSESSMENT

	IC Actual	Stirling Projections
Curb Weight (lb)	3760	TBD*
Acceleration (sec)		
0-30 mph	4.9	6.1
0-50 mph	10.0	14.8
0-60 mph	15.3	23.0
Fuel Economy (mpg)		
Urban	13.1	TBD
Highway	22.0	TBD

*To be determined.

Installation of the Stirling system commenced with removal of the internal combustion engine and transmission. Work performed to date on the Stirling installation is summarized in Table 6-2.

The vehicle build is on schedule for delivery to Langley Air Force Base on 31 August 1987.

TABLE 6-2
D-150 STIRLING INSTALLATION STATUS
(30 JUNE 1987)

Item	Comments
Engine mounts fabricated	Use original IC mount pads to reduce noise and vibration
Accessory brackets designed and fabricated	Provide easy access for repair and maintenance
Electric drive power brake unit selected and installed	Will also provide hydraulic power for combustion air blower variator
Webasto heater selected and installed	Phase I heater experience undesirable
Engine control installation started	Located behind seat; terminal boxes located on each fenderwell
Transmisison rebuilt without lockup	Eliminates trailer-hitching experienced with Phase I vehicle
Preliminary safety and configuration reviews held with NASA and Air Force MEEPs	
Engine trial fit achieved to ensure acceptable component positioning	

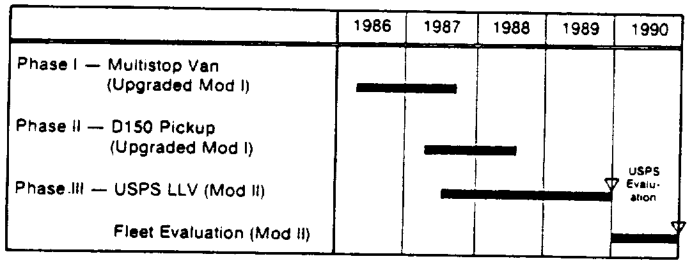


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Fig. 6-1 NASA Technology Utilization Van Program Summary Schedule

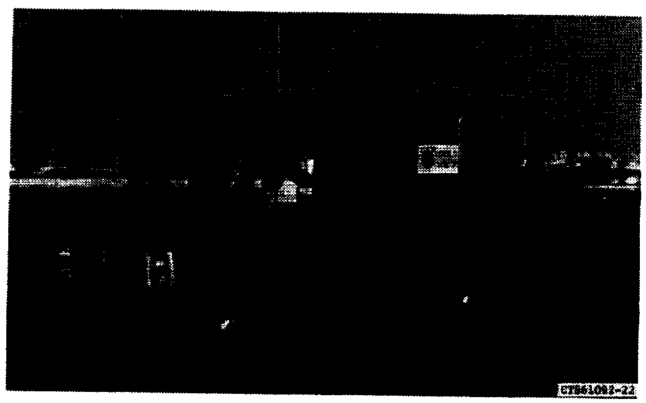

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Fig. 6-2 Air Force Multistop Van

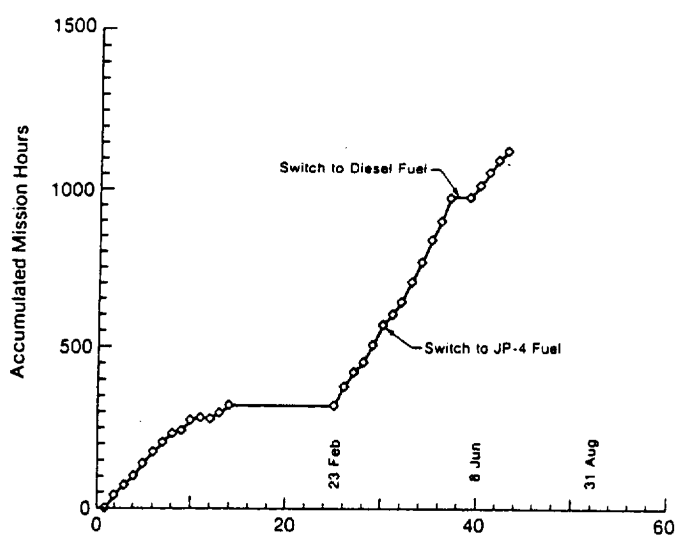

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Fig. 6-3 Stirling-Powered Van USAF Mission Progress History

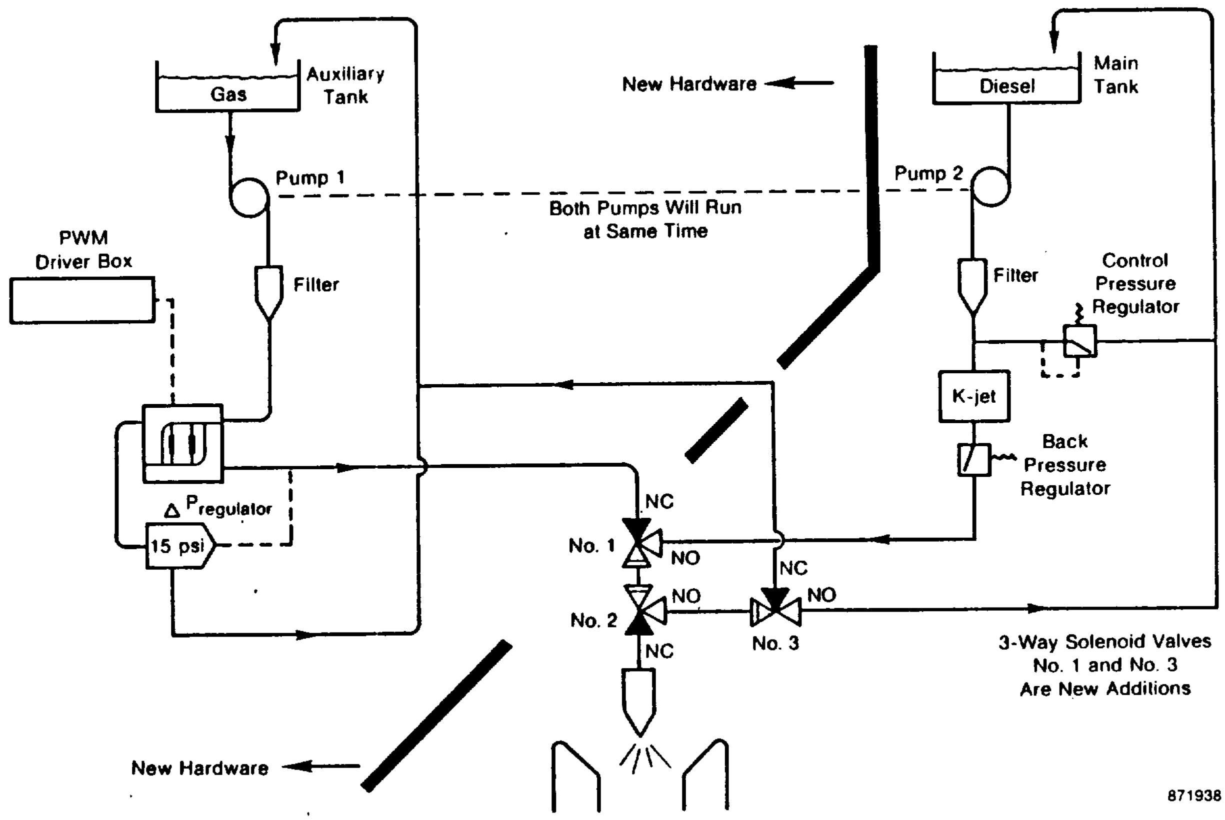

Fig. 6-4 Air Force Van Unleaded Gasoline Start/Diesel Running Fuel System

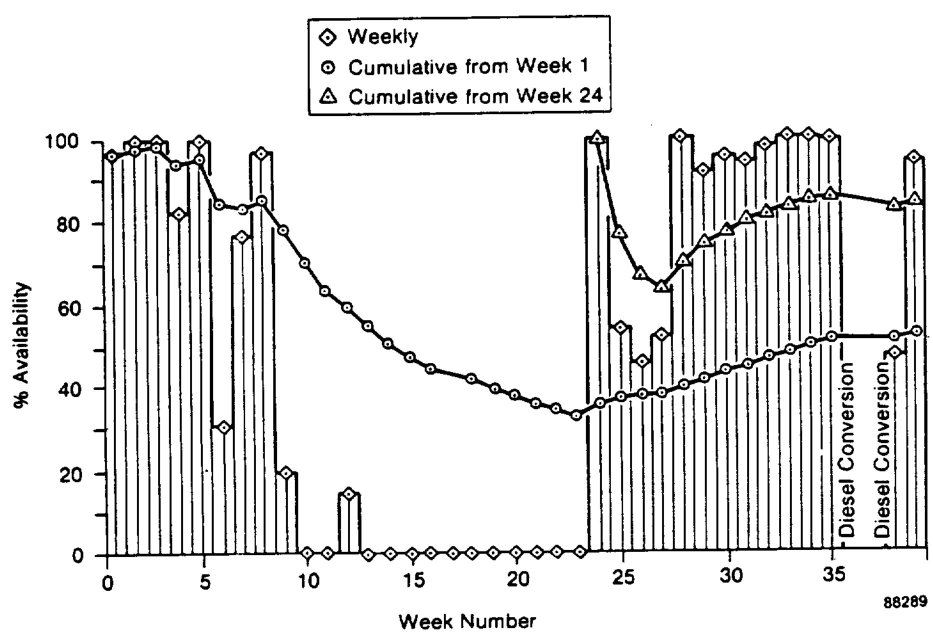

Fig. 6-5 Stirling Powered Van Program Availability Rate

Quality Assurance Overview

The status of the ASE Program Quality Assurance Reports (QARs) as of 30 June 1987 is presented below:

Open QARs (pending further analysis and/or NASA approval:	561
Closed QARs (total to date)	2090
P-40 QARs	272
Mod I QARs	631
Upgraded Mod I QARs	1203
Preliminary Mod II QARs (durability rig hardware)	49
Mod II QARs	455
Total QARs in system	2651

Program QAR activity for the first half of 1987 is as follows:

New QARs (for last six months)	382
P-40 QARs	0
Mod I QARs	5
Upgraded Mod I QARs	242
Preliminary Mod II QARs (durability rig hardware)	0
Mod II QARs	132

Mod I QAR Experience

A summary of trend-setting problems documented via the QAR system is presented in Table 7-1* and Figures 7-1 through 7-4. Problems are defined as items that 1) cause an engine to stop running; 2) prevent an engine from being started; or 3) cause degradation in engine performance. Problems that fall into these categories must be minimized to provide acceptable engine performance and maximize the mean time between failures.

Major trend-setting problems identified for individual units/assemblies that were established prior to 30 June 1983 are shown in comparison with the results of this reporting period and that of previous semiannual report periods.

Table 7-2 is a summary of the operating times versus failures for all active ASE Program Mod I/Mod II engines.

TABLE 7-2
MOD I/MOD II
OPERATING TIMES VERSUS FAILURES
AS OF JUNE 30, 1987

Engine No.				
Mod I	Upgraded Mod I	Mod II	Operation Time (hr)	Mean Operating Time to Failure (hr)
3			2376	132
	5		2848	73
	6		4060	406
7			4480	1120
	8		1429	65
	9		414	59
	10		202	40
	11		115	--
		1	263*	--

*Since end of characterization test (275 hr), total engine time = 538 hours

*Table 7-1 is on the following page.

TABLE 7-1

MAJOR PROBLEMS SUMMARY

Established Prior to 6/30/83		% of Total	Reports from 7/1/83-12/31/83	% of Total	Reports from 1/1/84-6/30/84	% of Total	Reports from 7/1/84-12/31/84	% of Total	Reports from 1/1/85-6/30/85	% of Total
Moog Valve	19	76.0	1	4.0	1	4.0	1	4.0	2	4.0
Heater Head	13	40.8	3	9.4	3	9.4	5	15.6	6	18.7
Check Valves	8	32.0	3	12.0	2	8.0	4	16.0	3	12.0
Combustion Blower	12	41.3	6	20.7	6	20.7	3	10.3	1	3.5
Fuel Nozzle	13	19.7	6	9.1	13	19.7	5	7.6	5	7.6
Igniter	5	45.4	1	9.1	0	--	2	18.2	0	--
Preheater	7	22.6	7	22.6	1	3.2	7	22.6	1	3.2
Atomizing Air Comp./Servo-Oil Pump	6	50.0	1	8.3	2	16.7	1	8.3	2	16.7
Combustor	7	18.0	4	10.2	2	5.1	4	10.2	5	12.8
Flameshield	6	24.0	3	12.0	0	--	10	40.0	4	16.0
PL Seal Assy.	8	24.2	3	9.1	8	24.3	7	21.2	1	3.0
Crankcase/Bedplate	0	--	2	40.0	0	--	1	20.0	2	40.0
Piston Rod	0	--	3	30.0	4	40.0	1	10.0	1	10.0
Gast Atomizing Air Comp.	-	--	-	--	-	--	-	--	-	--
Oil Pump	-	--	-	--	-	--	-	--	-	--
DEC	-	--	-	--	-	--	-	--	-	--

	Reports from 7/1/85-12/31/85	% of Total	Reports from 1/1/86-6/30/86	% of Total	Reports from 7/1/86-12/31/86	% of Total	Reports from 1/1/87-6/30/87	% of Total	Reports from 6/30/87-12/31/87
Moog Valve	2	8.0	0	--	0	--	- NO LONGER USED -		
Heater Head	0	--	2	6.3	0	--	0	--	
Check Valves	2	8.0	3	12.0	0	--	0	--	
Combustion Blower	1	3.5	0	--	0	--	0	--	
Fuel Nozzle	13	19.7	9	13.6	1	1.5	1	1.5	
Igniter	2	18.2	0	--	0	--	1	9.1	
Preheater	5	16.1	3	9.7	0	--	0	--	
Atomizing Air Comp./Servo-Oil Pump	0	--	- NO LONGER USED -						
Combustor	12	30.8	1	2.6	3	7.8	1	2.5	
Flameshield	2	8.0	0	--	0	--	0	--	
PL Seal Assy.	6	18.2	0	--	0	--	0	--	
Crankcase/Bedplate	0	--	0	--	0	--	0	--	
Piston Rod	1	10.0	0	--	0	--	0	--	
Gast Atomizing Air Comp.	0	--	0	--	0	--	5	100	
Oil Pump	0	--	0	--	0	--	8	100	
DEC	0	--	0	--	0	--	5	100	

Mod I hours accumulated prior to 6/30/83	- 2689	% of hours - 15
Mod I hours accumulated from 7/1/83 to 12/31/83	- 1881	% of hours - 11
Mod I hours accumulated from 1/1/84 to 6/30/84	- 1848	% of hours - 10
Mod I hours accumulated from 7/1/84 to 12/31/84	- 2263	% of hours - 13
Mod I hours accumulated from 1/1/85 to 6/30/85	- 2731	% of hours - 15
Mod I hours accumulated from 7/1/85 to 12/31/85	- 2787	% of hours - 16
Mod I hours accumulated from 1/1/86 to 6/30/86	- 1623	% of hours - 9
Mod I hours accumulated from 7/1/86 to 12/30/86	- 766	% of hours - 4
Mod I hours accumulated from 1/1/87 to 6/30/87	- 1247	% of hours - 7
Total Engine Hours (after Acceptance Test)	17835	100

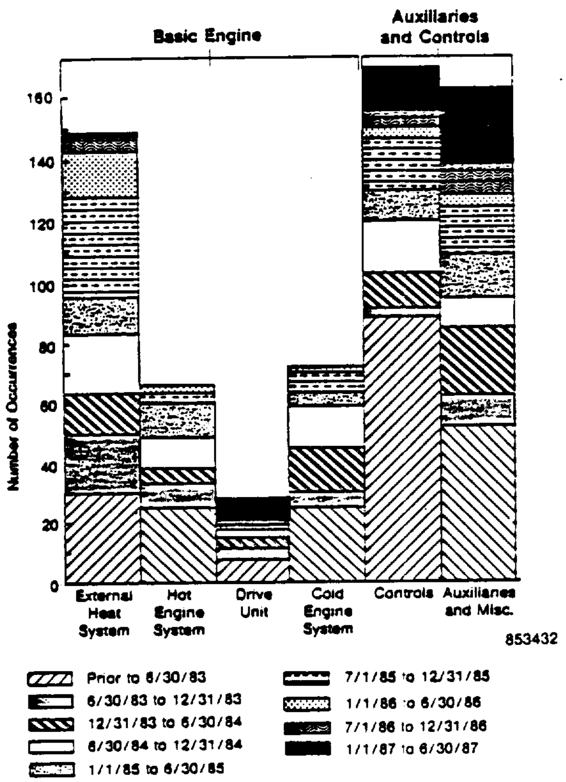

Fig. 7-1 Major Mod I Engine System Failures and Discrepancies through June 30, 1987

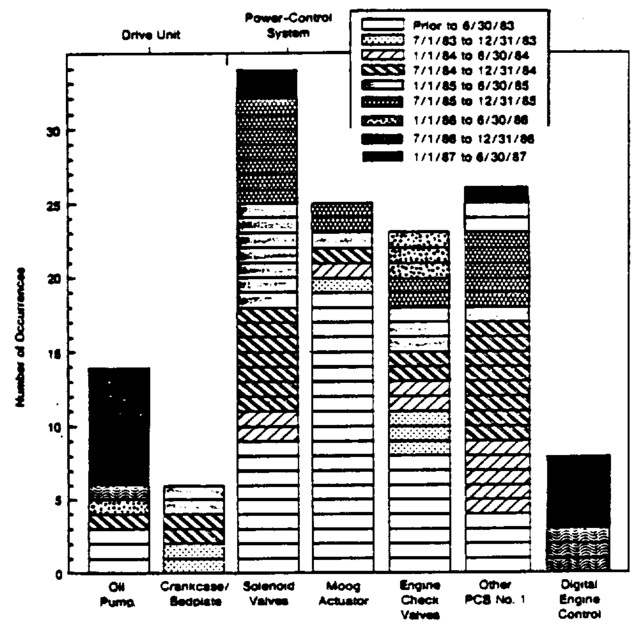

Fig. 7-2 Mod I Drive Unit and Power Control System Failures and Discrepancies through June 30, 1987

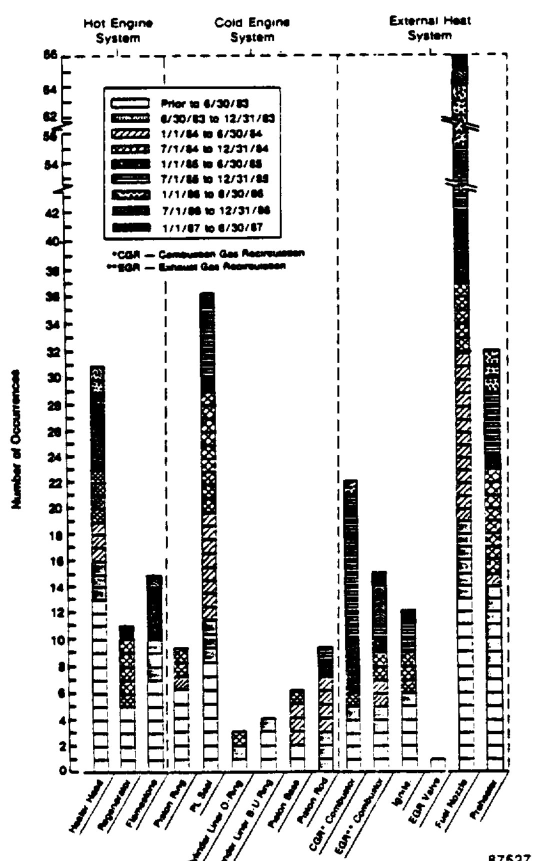

Fig. 7-3 Mod I Hot Engine, Cold Engine, and EHS Failures and Discrepancies through June 30, 1987

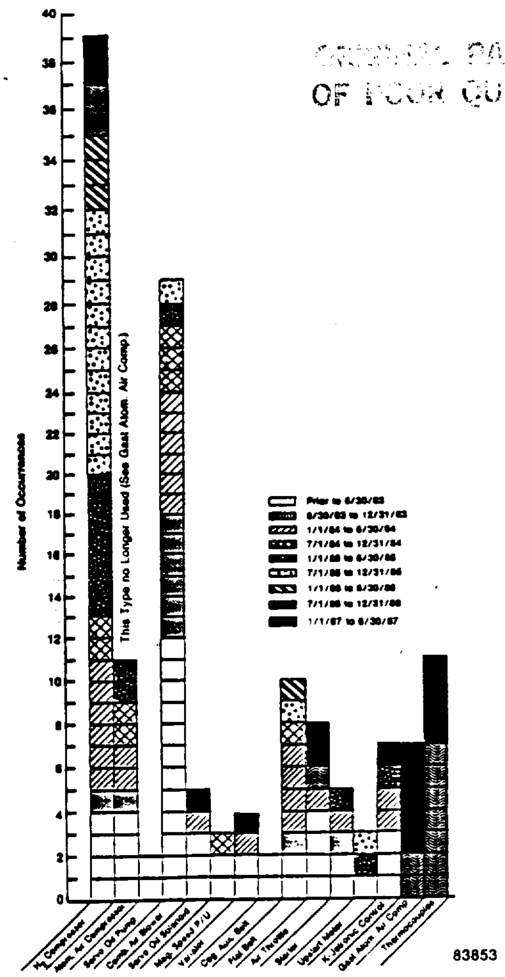

Fig. 7-4 Mod I Auxiliaries and Miscellaneous Failures and Discrepancies through June 30, 1987

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R. Farrell, A. Richey, and J. Mundy

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968 Albany-Shaker Road
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16. Abstract

This is the twelfth Semiannual Technical Progress Report prepared under the Automotive Stirling Engine (ASE) Development Program. It covers the thirty-fourth and thirty-fifth quarters of activity after award of the contract. Quarterly Technical Progress Reports related program activities from the first through the thirteenth quarters; thereafter, reporting was changed to a Semiannual format.

This report summarizes the study of high-power kinematic Stirling engines for transportation use, testing of Mod I and Mod II Stirling engines, and component development activities. Mod II development testing included performance, emissions, and noise as well as the impact of varying regenerator porosity, working gas, and heater head geometry. Mod I engines were used for Mod II component development and to obtain independent party (U.S. Air Force) evaluation of Stirling engine vehicle performance.

17. Key Words (Suggested by Author(s))
automotive Stirling engine, Mod I engine, upgraded Mod I engine, seals, reference engine, NASA Technology Utilization van, Mod II engine, heater head, emissions, alternate fuels, and value analysis/ value engineering

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